Hydrogeology and Water Quality at Bent Creek Research Station, Buncombe County, North Carolina, 2002 - 2009

Prepared in cooperation with the U.S. Geological Survey, North Carolina Water Science Center

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N.C. Department of Environment and Natural Resources
Division of Water Quality

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by Ted R. Campbell

ABSTRACT

A comprehensive multi-year hydrogeologic investigation (September 2002 to August 2009) was conducted in the Bent Creek Experimental Forest watershed in Buncombe County, North Carolina, as part of the North Carolina Department of Environment and Natural Resources and U.S. Geological Survey (USGS) cooperative Piedmont-Mountain Resource Evaluation Program (REP). The Bent Creek Research Station (BCRS) was installed to evaluate groundwater availability, movement, and quality in a regolith-fractured rock flow system dominated by mica schist geology. The site lies within the Blue Ridge physiographic province characterized by complex geology consisting of metamorphosed, deformed, fractured, and weathered meta-sedimentary and intrusive rocks. The BCRS is one of ten hydrogeologic research stations installed in the Piedmont and Mountains as part of the REP.

The BCRS is comprised of one stream gage, 7 rock cores, 15 piezometers, and 6 well clusters along a mile long transect from topographic highs in recharge areas to topographic lows in discharge areas. Each well cluster consists of three wells open to different zones within the groundwater system: upper regolith, lower regolith, and fractured bedrock. Two aquifer pumping tests (72 and 45 hour) were conducted in different portions of the groundwater flow system to evaluate hydraulic interconnectivity.

Groundwater occurred within a three-part system: upper regolith, lower regolith, and fractured bedrock. The upper regolith system (2 to 38 feet thick, median = 23 feet) has a high porosity and variable permeability and consisted of sandy, clayey, silty residuum-saprolite. The lower regolith system (5 to 46 feet, median = 19 feet) has a variable porosity and high permeability and consisted of partially weathered transition zone material with both primary porosity (pore spaces) and secondary porosity (rock partings and veins). Fractured bedrock occurred at a depth of 33 to 60 feet below land surface and generally contained few primary openings. Interlayering of saprolite, transition zone material, and un-weathered bedrock occurred at 3 of 7 cored locations and was due in large part to interlayered parent rock.

The lower regolith (median well yield = 5 gallons per minute (gpm) and hydraulic conductivity = 8 feet per day) had a much higher permeability than the upper regolith (median well yield = 1.5 gpm and hydraulic conductivity = 2 feet per day). Bedrock well yields ranged from less than 0.5 to 40 gpm (median = 1 gpm and average = 7 gpm). Rock coring, heat pulse flow measurements, and optical televiewer imaging indicate relatively few primary (open and significant) fractures at 7 well locations. Results from a 45-hour aquifer pumping test support this assessment and demonstrated a lack of hydraulic connectivity between the pumped bedrock well and two bedrock wells located within 1500 feet, and minimal, sluggish connectivity between the pumped bedrock well and overlying regolith wells.

The dominant lithology at the BCRS is well-foliated mica schist, interlayered with lesser amounts of poorly-foliated biotite gneiss/metagraywacke and migmatite. Bedrock foliations strike predominantly to the NE, dipping to the NW and SE at angles between 25 and 85 degrees. Bedrock fractures generally cross cut foliation and strike predominantly NW, dipping to the NE or SW at angles between 50 and 70 degrees. Less often, fractures are parallel to foliation or are of stress relief type.

Groundwater flow at BCRS generally is from topographic highs to lows, consistent with conceptual models of flow in the Blue Ridge and Piedmont physiographic provinces. Vertical gradients generally are downward in upslope and midslope recharge areas and upward in lower lying discharge areas. Rainfall events produced a rapid, temporary increase in potentiometric heads in upper and lower regolith wells that dissipated within about 7 days. Water temperature and vertical head gradients in clustered wells were used to demonstrate upwelling from the deeper to the shallower groundwater system during rain events in a low-lying discharge area. Data indicate that at least some recharge infiltrates to the water table within 0.5 to 2 days of rainfall events in two low-lying discharge areas. Age estimates of groundwater in four bedrock wells ranged from about 20 to 50 years, and, within a given well, a mixture of ages was common (including water less than 2 years old in at least one upslope bedrock well). Observing a mixture of older and younger waters within bedrock wells is consistent with

the regional conceptual model in which multiple potential flow paths (and source waters) contribute to the total volume of water in a bedrock well.

Bent Creek, a 3rd order stream that drains the larger watershed, is a major control on groundwater flow direction in the Boyd Branch basin. Locally, groundwater discharges to some reaches of Boyd Branch, a small, weakly incised 2nd order tributary to Bent Creek, and groundwater under-flow occurred in one measured reach of the stream. The water table occurred at a depth of about 3 to 32 feet below land surface and varied seasonally and with topographic setting, and vertical head gradients between the shallow and bedrock flow system typically were 1 to 2 ft except in one discharge location with a 12 ft difference. Water levels tended to be lowest in late summer when evapotranspiration effects tend to be greater than recharge, and highest in late winter.

The dominant water type for bedrock wells is calcium bicarbonate, and for streams and regolith wells is sodium/magnesium-bicarbonate. Ground and surface water are relatively soft, of high quality, and suitable for most domestic and industrial-use purposes. Values of pH, calcium, magnesium, and sulfate were higher than typical regional levels in some of the BCRS bedrock wells, due in part to the rock type and local geochemistry. Deeper groundwater contained higher amounts of dissolved ions than shallow groundwater due to increased residence time for the dissolution of minerals.

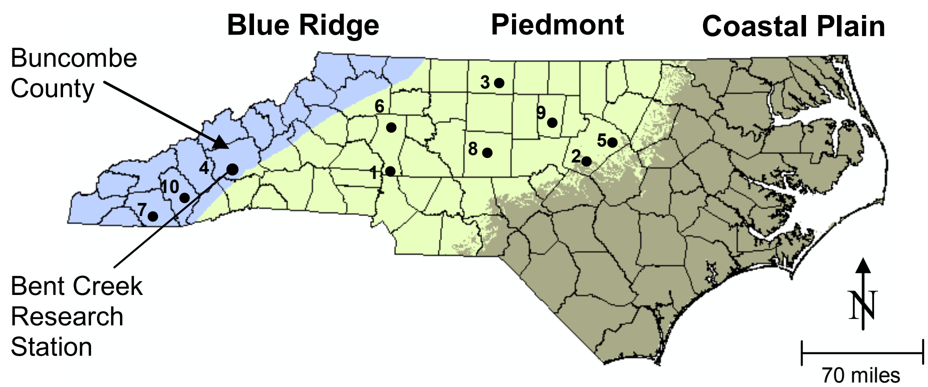
INTRODUCTION

This investigation is part of a multi-year cooperative partnership with the N.C. Department of Environment and Natural Resources Division of Water Quality (NCDENR DWQ) and the U.S. Geological Survey (USGS) to characterize ambient quality and movement of groundwater in the Piedmont and Blue Ridge physiographic provinces of North Carolina (Daniel and Dahlen, 2002). The study was conducted at the Bent Creek Research Station (BCRS) (fig. 1) located in the Pisgah National Forest in southwest Buncombe County, a setting characterized by mica schist and biotite gneiss. About 5 percent of the hydrogeologic units within the Piedmont-Mountains are classified as schist, and about 18 percent are classified as mafic (to include biotite) gneiss (Daniel and Dahlen, 2002).

The BCRS site was selected to better understand groundwater quality and movement within the weathered and unweathered parts of the flow system in a mountain setting underlain by interlayered mica schist and biotite gneiss. Results of this study will be integrated with findings from nine other sites (fig. 1) across the Piedmont-Mountains to better understand, map, and protect the State and Nation's water resources and to help advance a number of key objectives (Pippin and others, 2008; Chapman and others, 2005; Daniel and Dahlen, 2002) of the DWQ-USGS partnership. Specifically, the BCRS findings will be used to develop a better working understanding of:

- the overall hydrogeologic framework of the Piedmont and Blue Ridge physiographic provinces;
- the three portions of the fractured rock groundwater flow system and their hydraulic connectivity in different geologic and geomorphologic settings;
- recharge and discharge in fractured rock systems and their effect on ground- and surface-water quality;
- potential groundwater storage in fractured rock settings; and
- the interconnection between surface- and groundwater flow systems and their effects on water quality.

Findings will also be incorporated into a comprehensive groundwater database for the region.



Map number	Research station
1	Langtree Peninsula at Lake Norman
2	N.C. State University Lake Wheeler Road Field Laboratory
3	N.C. State University Upper Piedmont
4	Bent Creek Experimental Forest Research Station
5	Raleigh Hydrogeologic Research Station
6	Allison Woods Hydrogeologic Research Station
7	Coweeta Hydrogeologic Research Station
8	N.C. Zoological Park Research Station
9	Duke Forest Research Station
10	Western Carolina University Research Station

Figure 1. Location of Piedmont-Mountains hydrogeologic research stations, including Bent Creek Research Station, and North Carolina physiographic provinces.

Background and Previous Studies

Groundwater in the Piedmont-Mountains of North Carolina occurs in complex hydrogeologic terranes that consist of metamorphosed igneous, sedimentary, and volcanic rocks. Rocks within these terranes have undergone multiple deformations and often are interlayered at varying scales (inches to miles). Local stratigraphy is shaped by the movement (tectonic, erosional, alluvial, and fluvial processes) and alteration (chemical and mechanical weathering) of these rocks.

Piedmont-Mountains groundwater generally occurs in a two-part flow system - shallow flow through weathered regolith and deeper flow through fractured bedrock. Some researchers have referred to a three-part flow system in which the highly permeable transition zone is defined as a separate unit (Chapman and others, 2005). In their hydrogeologic characterization of the Piedmont, Harned and Daniel (1992) described the nature of the transition zone between regolith and bedrock and the relationship between storage in the granular, highly porous regolith and fracture conduits in the underlying bedrock (fig. 2). In a summary of findings, Daniel and Dahlen (2002) noted regolith thicknesses in the region from zero (at rock outcroppings) to more than 150 feet (ft), depending on parent rock type, topography, climate, and groundwater chemistry, and observed that the number of fractures and size of fracture openings in consolidated bedrock decreases with depth (openings tend to be very small below about 750 feet due to pressure from the overlying material).

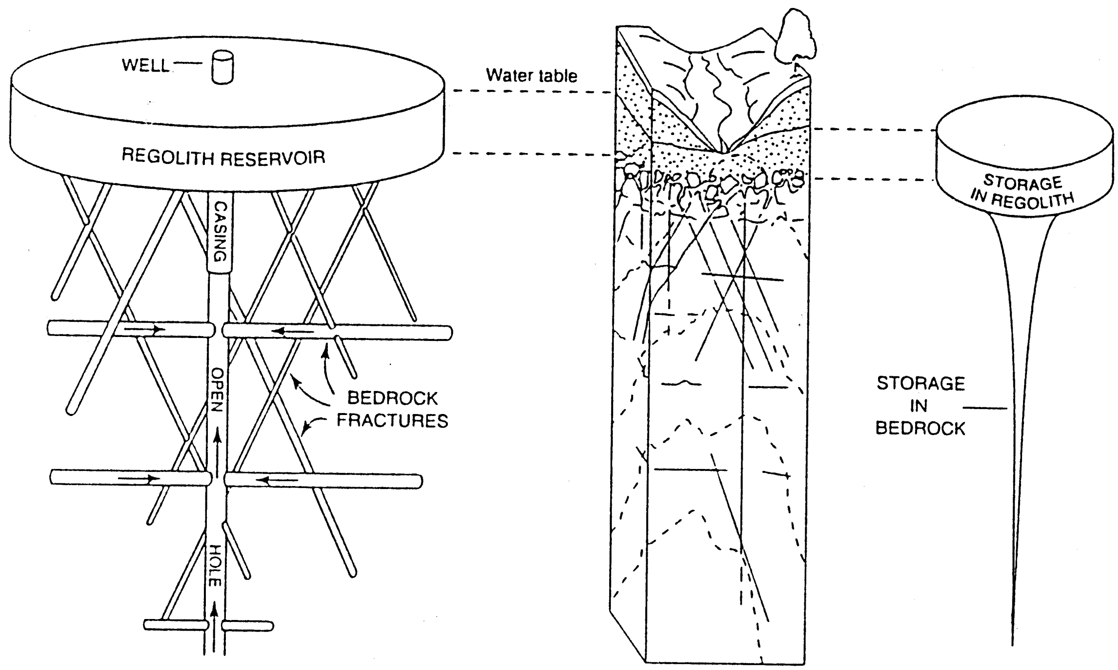


Figure 2. Schematic showing regolith storage and bedrock fracture conduits in the fractured rock aquifer system of the Piedmont and Mountains of North Carolina (from Harned and Daniel, 1992).

Various researchers have described the hydrogeology and conceptual groundwater framework of the Piedmont-Mountain region of North Carolina, including LeGrand (1967), Heath (1983, 1984), Swain and others, (1996), and Daniel and Dahlen (2002). Mesko and others (1999) published a description of Blue Ridge and Piedmont hydrogeology and hydrogeologic terranes, including geologic and water-bearing properties. Daniel and Payne (1990) compiled a hydrogeologic unit map for the region. LeGrand (2004) published a conceptual model of the region that summarized a number of commonly understood hydrogeologic generalizations. His model describes groundwater flow as occurring within individual slope-aquifer compartments that correspond to areas between topographic divides and that are open-ended down slope. These slope-aquifer systems can serve to isolate ambient (un-pumped, gravity-drained) flow in one slope-aquifer compartment from that of a neighboring compartment. Seaton and Burbey (2005) described the influence of ancient thrust faults on the hydrogeology of the Blue Ridge Province in southwestern Virginia and documented the occurrence of a shallow saprolite aquifer separated from a high-permeability, high storage deeper fault-zone aquifer by a low-fracture permeability bedrock confining unit.

Daniel (1992) and Daniel and others (1997) statistically analyzed fracture permeability with depth in fractured rock of different topographic settings within the Piedmont of North Carolina. Daniel (1989) compiled well information from existing data in the Piedmont-Mountains and determined relationships between well yield and construction, topographic setting, hydrogeologic units, geologic belts, and other characteristics.

Chapman and others (2005) published findings from a PMREP station representing a well foliated, steeply dipping, felsic gneiss (Lake Wheeler Road, Wake County). The groundwater flow system was described, and hydraulic, flow, and water quality data were reported. Results generally support the conceptual model of groundwater flow in the region, with local variations in vertical gradients. Local upwelling of groundwater from the transition zone into the shallow regolith was observed after recharge events and subsequent rise in stage at a nearby tributary. Elevated nitrate concentrations were observed in groundwater, likely due to past agricultural activities in the study area.

Huffman and others (2006) compiled five years of hydrogeologic and water resource data for 4 PMREP research stations in the Piedmont and Blue Ridge physiographic provinces, including the Lake Wheeler Road station in Wake County, Langtree Peninsula in Iredell County (moderate to steeply dipping quartz diorite and weakly foliated biotite gneiss), Upper Piedmont in Rockingham County (gently to moderately dipping amphibolite and interlayered felsic gneiss), and Bent Creek in Buncombe County (moderate to steeply dipping schist and biotite gneiss). Data obtained from well installation at the 4 stations (110 wells), rock coring, borehole geophysics, periodic groundwater levels, water quality measurements, stream flow measurements, and slug tests were presented.

Pippin and others (2008) presented hydrogeologic, groundwater flow, and groundwater quality findings for the Langtree Peninsula PMREP research station in Iredell County. Results from six years of data support the general conceptual model of groundwater flow in the region - groundwater generally flowed from high to low topographic settings, groundwater discharged to a surface water boundary, and vertical hydraulic gradients generally were downward in recharge areas and upward in discharge areas. The dominant groundwater type - calcium bicarbonate - was similar in all three zones (regolith, transition zone, and bedrock) of the groundwater system. Recharge may occur seasonally over a period of several months or, after heavy rainfall, over a shorter period of a few to several weeks.

McSwain and others (2008) presented two years of hydrogeologic and water resource data for the PMREP Raleigh Hydrogeologic Research Station in Wake County. The site is underlain by the Rolesville batholith, a massive to weakly foliated granitic intrusion, which is, in turn, intruded by near vertical tabular basaltic diabase dikes. Data obtained from well installation, borehole geophysics, periodic groundwater levels, water quality measurements, and slug tests were presented. Groundwater-surface water relationships were evaluated using temperature and water quality measurements from drive points along a cross section of the adjacent Neuse River discharge area.

Groundwater recharge rates for the Piedmont and Blue Ridge of North Carolina were estimated by Heath (1994), Daniel and Sharpless (1983), Harned and Daniel (1987), and Mew and others (2002). Studies of groundwater recharge in the Central Piedmont have been made by Daniel (1996) and Daniel and Harned (1998). And Rutledge and Mesko (1996) evaluated hydrologic characteristics of shallow aquifer systems in three provinces, including the Blue Ridge, based on stream flow recessions and baseflow analyses.

Briel (1997) published a comprehensive evaluation of regional water quality data obtained from various sources from the Valley and Ridge (3734 wells), Piedmont (n = 13,498 wells), and Blue Ridge (n = 776 wells) physiographic provinces of the eastern U.S. Briel described the dominant chemical type in Blue Ridge groundwater as a mixed water containing calcium magnesium bicarbonate and sodium chloride. Trapp (1970) published an evaluation of geology and groundwater resources and quality in Buncombe (18 wells), Henderson (24 wells), Transylvania (14 wells), and Madison (14 wells) Counties, North Carolina. Trapp described groundwater in Buncombe County as having a dominant bicarbonate anion signature and varying cation ratios of calcium, magnesium, and sodium. Reid (1993) presented results of the National Uranium Resource Evaluation Program in which uranium and other inorganic constituents were analyzed from nearly 6000 wells across North Carolina. Campbell (2006a, 2008b, 2008) conducted regional studies in the Piedmont-Mountains to evaluate naturally occurring radionuclides in groundwater, including uranium, radium-226, radium-228, and radon-222; several areas underlain by granitic rocks were associated with elevated dissolved radon and, to a lesser degree, elevated dissolved uranium. Combined radium-226 + 228 were below regulatory limits in all sampled wells.

Geologic mapping of the Bent Creek watershed was published by Merschat and Carter (2002). Local, site-scale geologic mapping was conducted in the Boyd Branch sub-basin within the Bent Creek Experimental Forest by W. Burton (written communication, July 25, 2008). Unpublished soil maps and descriptions are available for the Bent Creek watershed (H. McNab, written communication, February 5, 2004).

Purpose and Scope

The purpose of this report is to present findings from a hydrogeologic investigation conducted from September 2002 to August 2009 at the BCRS, located within the Bent Creek watershed. The study focuses specifically on one part of the Bent Creek watershed – the Boyd Branch sub-basin (fig.

3). The sub-basin, hereinafter referred to as BCRS or study area, represents one geologic type area in the Piedmont-Mountains region. A type area is defined here as a representative geologic setting commonly found in other parts of the region and having transferability value. Over time, the DWQ-USGS partnership will compare groundwater availability, movement, and quality data from one type area to other type areas across the region.

Data used in this investigation were obtained from existing sources (for example, soil and geology maps) and from fieldwork conducted by the NCDWQ and USGS scientists between 2002 and 2009. Fieldwork included the following activities:

- rock coring was conducted at 7 locations
- 6 well clusters and an additional bedrock well (18 wells in all) were installed along a mile-long transect from topographic highs to lows to evaluate groundwater conditions; the well clusters were designed to measure different depths within the groundwater system and consist of an upper regolith, lower regolith, and bedrock well.
- 7 piezometer clusters were installed (15 piezometers in all) to monitor drawdowns during aquifer pumping tests
- borehole geophysical logs and direction adjusted optical televiewer images were collected in 6 bedrock wells
- stream and groundwater-quality samples were collected and analyzed periodically at various locations over 5 years
- monthly water levels were measured in study wells over a 6-year period
- age dates were analyzed for selected groundwater samples
- continuous, hourly groundwater level and groundwater quality monitoring was conducted over a 1-year period at one well cluster in a discharge area
- continuous, hourly temperatures were recorded in 3 well clusters, 1 shallow well, stream water, and streambank sediment over a 9-month period
- aquifer slug and pumping tests were conducted to evaluate the water-bearing properties of the groundwater system.

Study Area Location and Setting

The BCRS is located within the Boyd Branch sub-basin of the Bent Creek watershed, 11 miles south of the city of Asheville, in southwest Buncombe County in the Blue Ridge physiographic province of western North Carolina (fig. 3). The Blue Ridge physiographic province is part of the Appalachian Highlands, a mountainous range that extends from southern Canada to central Alabama with elevations ranging from about 6,800 to 2,000 feet above mean sea level (asl). The BCRS watershed is comprised of rugged, pristine, forested land that is owned and managed by the U.S. Forest Service for research and recreational uses.

The larger Bent Creek watershed, of which BCRS is part, covers an area of 8.7 mi^2 and is NE trending and trough-shaped, with steep slopes near the ridgeline drainage divide (about 3,600 feet asl) and milder slopes in the lower elevations along the valley floor (about 2,100 feet asl) (fig. 4). The natural erosion of weaker rock over very long periods of time has shaped topography in the basin. The weaker rock tends to occur in areas where faults, joints, and (or) fractures are present or in the vicinity of contacts between different rock types. These areas tend to erode, form, and shape natural drainage features within the basin. Streams and tributaries often are visible expressions of these underlying structures and the erosion process. Slope instability is not uncommon in steep terrains like Bent Creek, and Pomeroy (1991), Witt (2005), and Wooten and others (2009) have documented historic landslides within the Bent Creek watershed.

The BCRS watershed drains to Bent Creek, a tributary of the French Broad River, just south of Asheville (fig. 3). The French Broad is located on the western side of the Eastern Continental Divide and is thus part of the large network of rivers that form the Tennessee, Ohio, and Mississippi Rivers, which ultimately empty into the Gulf of Mexico.

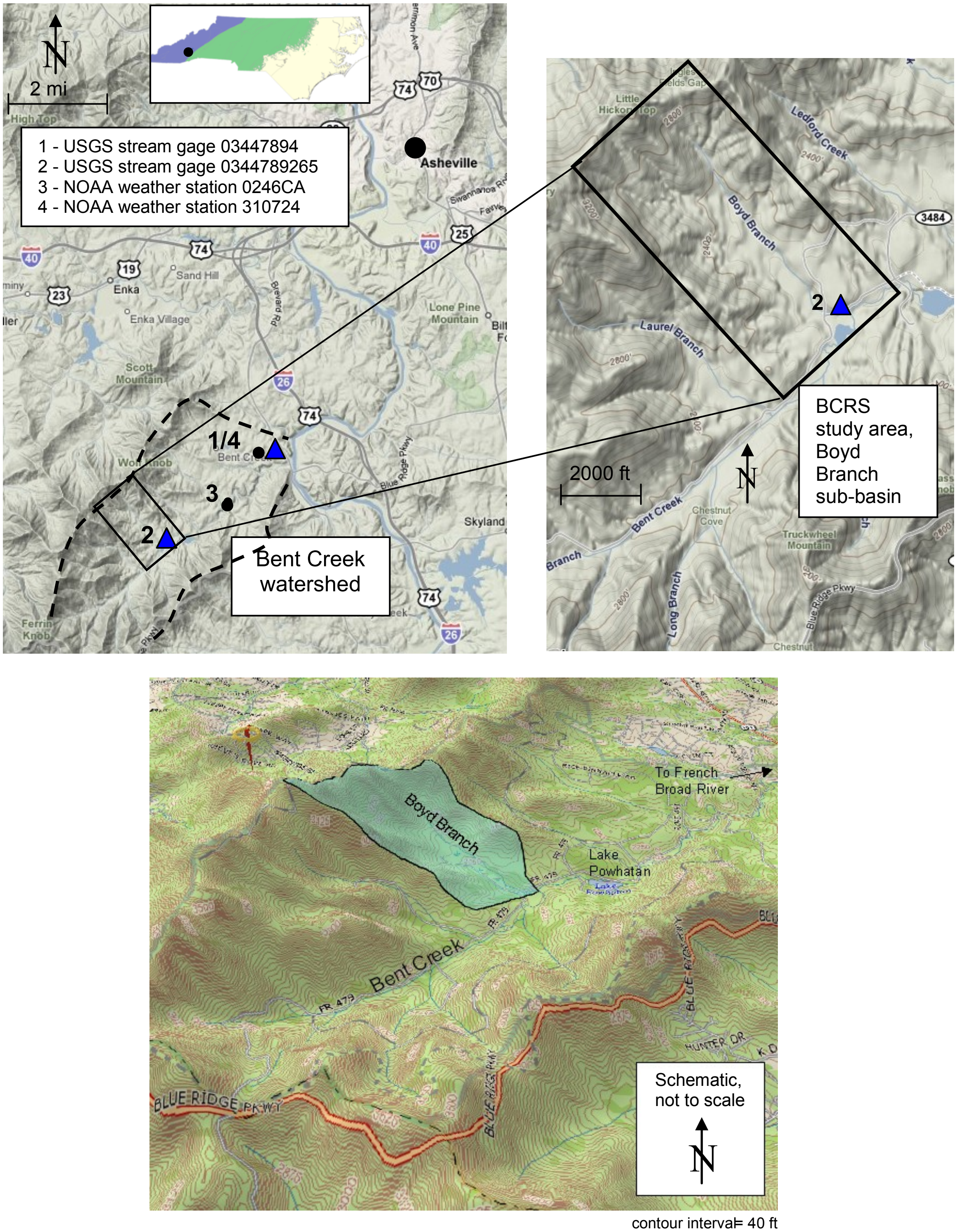


Figure. 3. Location of the Bent Creek Research Station in the Boyd Branch sub-basin, Bent Creek Experimental Forest watershed, North Carolina, and location of National Oceanic and Atmospheric Administration rain gages 0246C and 310724 and U.S. Geological Survey stream gages 03447894 and 0344789265.

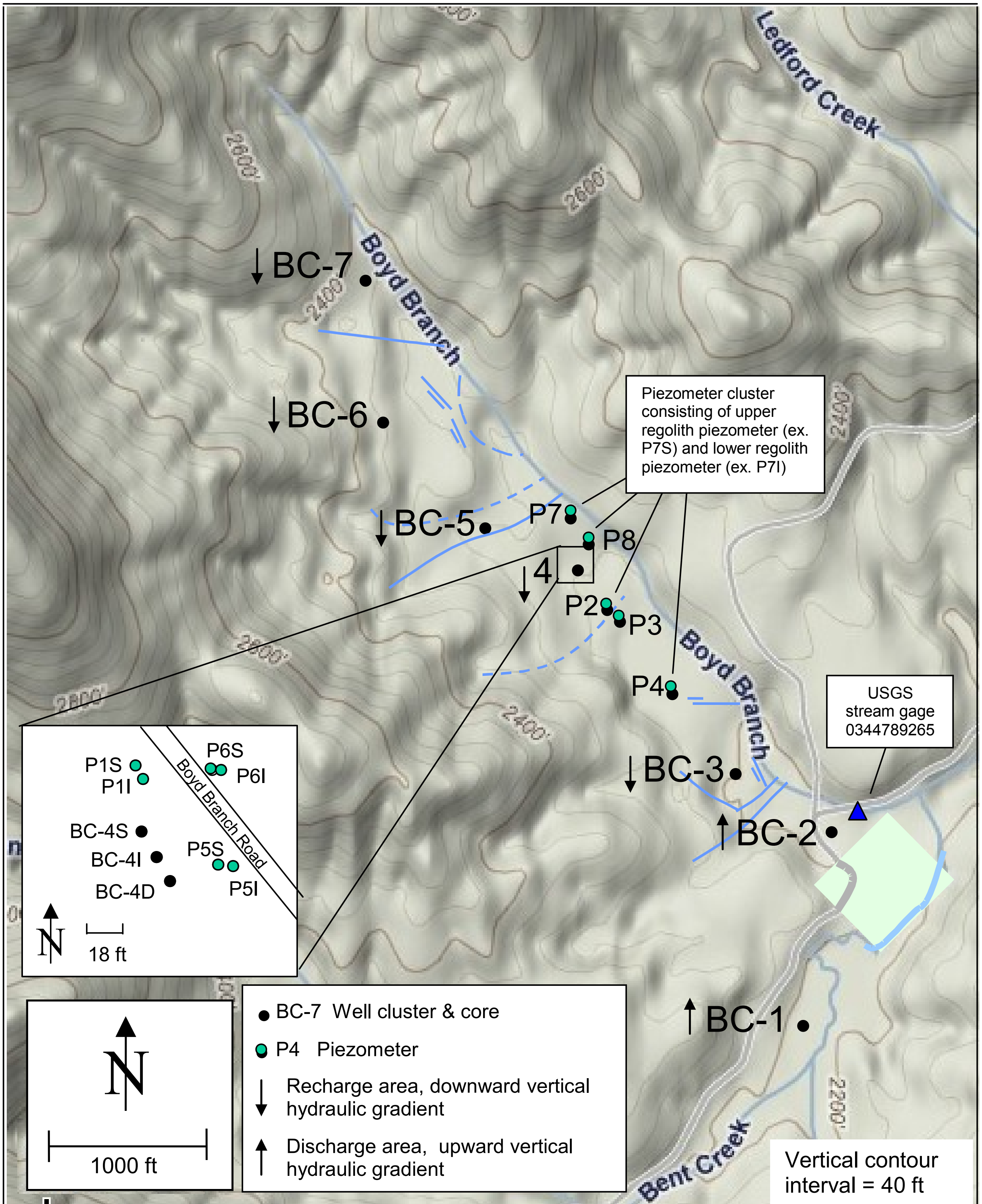


Figure 4. Topographic setting, well locations, and areas of recharge and discharge, Bent Creek Research Station, North Carolina.

The Boyd Branch sub-basin is situated in the north-central part of the Bent Creek watershed (fig. 3). It is a 1.1 mi^2 oblong-shaped basin, trending northwest, approximately perpendicular to Bent Creek (fig. 4). Elevations range from about 3,200 ft asl at the ridgeline to about 2,180 ft asl at the valley floor where Boyd Branch discharges into Bent Creek.

The Bent Creek watershed is underlain predominately by mica schist and muscovite-biotite gneiss (referred to as metagraywacke) of the Ashe Metamorphic Suite and Tallulah Falls Formation (Merschat and Carter, 2002). Within the BCRS area of investigation, mica schist is the predominate rock type, with slightly lesser amounts of interlayered migmatitic biotite gneiss. The site therefore represents a schist-gneiss “type area”, one of several geologic type areas being compared as part of a larger systematic evaluation of hydrogeologic settings across the region.

Methods of Investigation

The methods used for well installation, rock coring, borehole geophysical testing, water level measurements, water quality sampling, and slug and aquifer testing conducted during this investigation are described in the report of standard operating procedures for conducting hydrogeologic field investigations (NCDENR, DWQ, 2008). Additional site specific methods are presented here.

The BCRS consists of 6 well clusters and an additional bedrock well (18 wells in all) positioned along a high to low topographic transect within a “slope-aquifer” system similar to that described by LeGrand (2004). The well clusters were designed to evaluate groundwater conditions from recharge to discharge areas within a slope-aquifer sub-basin (Boyd Branch). The clusters consist of an upper regolith (saprolite) well, a lower regolith (transition zone) well, and an open hole bedrock well.
The well naming convention used in this study is as follows: all wells designated with “S” (for example, “BC-3S”) are upper regolith wells screened across saprolite material (with the exception of BC-1S, which is screened across alluvium/colluvium/transition zone material). All wells designated with “I” (for example, “BC-3I”) are lower regolith wells screened across transition zone material. And all wells designated with “D” (for example, “BC-3D”) are open borehole bedrock wells with surface casing seated about 3 to 10 feet into competent bedrock. Lower regolith well BC-6I was vandalized shortly after installation and could not be used, and upper regolith well BC-2S was damaged during construction and could be used only for measurement of water levels and selected field parameters. Seven piezometer clusters (consisting of an upper regolith piezometer and a lower regolith piezometer) (15 piezometers in all) were installed along two approximately perpendicular transects in the vicinity of an aquifer test site to measure detailed drawdown information and to map lateral groundwater movement in one representative recharge area of the BCRS.

To aid in well construction design and to better understand site geology, continuous soil and bedrock cores were collected at each well cluster location. Cores were collected using a wire-line coring rig and a 5-ft long, 2.5 inch inside diameter core barrel. Core descriptions were conducted on and off site, and included soil characteristics, rock type, fracture and foliation type and orientation, weathering, and other geologic features.

Monitoring wells were constructed using mud-rotary, air-rotary, and hollow-stem auger methods. Coarse sand was used as a filter pack around, and about 2 feet above, the screened interval to improve the hydraulic connection between the well and the aquifer. At least 2 feet of bentonite was placed as a seal on top of the sand pack, and the remaining annular space was filled with Portland cement grout to land surface. Steel protective casings with locking covers were installed on all wells.

Borehole geophysical logging was conducted in 6 bedrock wells and included caliper, natural gamma, temperature, fluid resistivity, electrical resistivity, and heat pulse flow meter logs. Direction-adjusted optical televiewer images were obtained to determine foliation and fracture orientations.

Water levels were measured to an accuracy of 0.01 ft approximately monthly using electronic water level meters referenced to a measuring point at the top of casing. Measuring points were surveyed and referenced to North American Vertical Datum of 1988. Hourly water levels (and temperature) were recorded using a float tape or pressure transducer at wells BC-2S, -2I, and -2D from August 2004 to December 2005 and at BC-7S from May 2008 to August 2009. In addition, hourly water quality parameters (pH, temperature, specific conductance (SC), and dissolved oxygen (DO)) were measured with a downhole multimeter during this period to determine seasonal fluctuations and to evaluate short-term fluctuations and response to recharge. The multimeter probe was cleaned and calibrated at least once per month following USGS guidelines (Wagner and others, 2006).

Submersible temperature data loggers were placed in selected cluster wells, stream, and streambank locations to evaluate groundwater-surface water relationships in recharge and discharge areas and to evaluate the relationship between the shallow regolith and deeper bedrock flow system. The loggers were placed on the stream bottom, 2 to 5 feet into the stream bank sediment, or were suspended downhole within the screened interval, about 2 feet from the bottom of the well, or near a primary fracture in bedrock wells. Hourly temperature readings were recorded during selected periods between July 2008 and February 2009. Hourly air temperatures and hourly rainfall data were obtained from the National Oceanic and Atmospheric Administration weather stations 0426CA (about 1.2 miles N-NE of BCRS) and KAVL (about 5.9 miles SE of BCRS).

Slug tests were conducted at selected wells to evaluate horizontal hydraulic conductivity in the vicinity of the well. The slug consisted of a sealed 5-ft long, 3-inch diameter PVC pipe that was quickly submerged (falling head test) or removed from the well water (rising head test). A pressure transducer and data logger recorded the change in water level over time in response to the displaced water until levels returned to within 95 percent of the pre-test level. The time-water level data were analyzed using the Bouwer and Rice (1976) method which accounts for partial penetration effects and changing aquifer thickness. Assumptions inherent in the method are that the aquifer is porous, isotropic (no directional variation in properties), effects of elastic storage are negligible, and the position of the water table does not change during the test. The aquifer thickness was approximated by the total regolith thickness for tests on upper and lower regolith wells or the length of the open borehole for tests on bedrock wells.

A 72-hour constant-rate aquifer pumping test was conducted at BC-4I (fig. 4) to evaluate aquifer characteristics in the regolith and to determine the degree of connectivity between upper regolith, lower regolith, and fractured bedrock in this area. A 4-inch diameter, variable speed submersible pump was placed in BC-4I to a depth of 41 ft, and a 1.5 inch diameter polyethylene hose was used as a discharge line. A digital, in-line flow meter was used to estimate pump discharge rates, and the rates were manually verified using a graduated 5-gallon bucket and stopwatch. Care was taken to ensure a steady, continuous, uniform flow rate throughout the test, and discharge water was routed away from areas of local groundwater recharge and into Boyd Branch approximately 300 feet downgradient to the east. Water levels were measured by an In-Situ® Hermit data logger attached to In-Situ® pressure transducers, In-Situ® miniTROLLs, or, for outlying wells, by handheld electric tapes. Conditions were dry throughout the test and a minor seasonal drift in water levels was noted in distant background wells BC-3 and BC-7 (fig. 4) for comparison to test wells in proximity to pumping. Staff gage measurements made during the test did not reveal observable drawdown in Boyd Branch. No attempt was made to measure potential changes in flow rates in Boyd Branch during the aquifer test.

Regolith wells installed within about 50 feet of the pumping well were used to observe the delay in the time-drawdown curve at individual wells and to analyze aquifer characteristics in this area. These wells were positioned in a radial pattern and along perpendicular transects to observe potential anisotropy and the shape and extent of the cone of pumping influence. If weathered-in-place parent rock retains relict foliations and these foliations are preferred pathways, then both the saprolite and transition zone likely will be anisotropic, both horizontally and vertically. More distant wells were used to observe the distance that the cone of depression expanded during the test.

A 45-hour constant-rate aquifer pumping test was also conducted at BC-4D, an open-hole bedrock well, from June 20 to 22, 2006 to evaluate the relative hydraulic connectivity between the deeper fractured rock and the shallow regolith flow system. The pump and discharge line configuration were the same as that used in the aquifer test at BC-4I, and the well was pumped at a constant flow rate of about 6 gpm. Well BC-4D is cased to 61 feet bls and is 501 feet deep. Water levels were measured throughout the test in the same 19 wells and piezometers used during the aquifer test at BC-4I. Water levels were measured by an In-Situ® Hermit data logger attached to In-Situ® pressure transducers, In-Situ® miniTROLLs, or, for outlying wells, by handheld electric tapes. Flow rates were measured at regular intervals throughout the test using manual and instrumented totalizer methods. Conditions were mostly dry throughout the test and minor seasonal drift in water levels was adjusted during data analysis using water level trends in distant background wells for comparison.

Groundwater quality samples were collected using variable-speed, submersible 2-inch diameter pumps and smaller, single-speed plastic submersible pumps. At least 3 well volumes of water were purged and field parameters were stable prior to sample collection at regolith wells. Removing 3 well volumes from the deep, 6-inch diameter bedrock wells was impractical using the low-rate sample pumps, so at least one well volume of water was removed and field parameters were stable prior to sampling. To obtain a representative sample, the sample pump was lowered to a mid-screen depth in regolith wells. Through strategic pump placement, water quality samples collected from bedrock wells were taken at a depth corresponding to the most predominant fracture in the borehole (Chapman and others, 2005). Even still, sample water collected from a bedrock well is a composite of water from multiple fractures, with each fracture representing a flow path of varying length originating in one or more recharge areas.

For age dating purposes selected groundwater samples were analyzed for chlorofluorocarbons (CFCs) and tritium-helium. CFCs are stable anthropogenic compounds used as refrigerants since the 1930s and are commonly used to date the age of relatively young (less than about 50 years) groundwater. Three CFCs (CFC-11, -12, and -113) were measured and used in age dating models to determine an apparent mean-estimated age. The CFC-based age estimate represented the mean residence time composite for the sample and typically was presented as a range. Unless noted, the estimated ages do not account for mixing scenarios that can occur in wells with large open intervals or multiple producing fractures.

Tritium and helium were sampled and used to estimate the youngest component of groundwater ages. Tritium is a radioactive element that entered groundwater systems after atmospheric testing of nuclear devices began in 1952. Tritiogenic helium-3 is derived from the radioactive decay of tritium, and the ratio of tritium-helium in the water sample may be used to estimate the age of younger groundwater to within one year.

As part of the age dating methodology, dominant fracture sets were isolated and sampled using an inflatable packer system at two bedrock wells. For quality control, a halon tracer had been mixed with compressed air during the original air-rotary well drilling activities to indicate whether or not modern air containing CFC’s was introduced to the groundwater during well installation. If the halon tracer was not present in the groundwater sample, then the sample generally is considered representative of the natural flow system and an age was estimated. Because of the complex three-dimensional nature of fractured groundwater flow, bedrock wells inherently draw water that is a composite of various source waters, and a range of ages may be expected. Sampling and analysis methods are provided in the USGS Reston Chlorofluorocarbon Laboratory website (http://water.usgs.gov/lab/cfc/).

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The geologic mapping and personal communications of Carl Merschat (North Carolina Geological Survey (NCGS), Mark Carter (formerly with NCGS), and Bill Burton (USGS, Reston) were instrumental in developing an understanding of the geologic framework of the study area. The detailed core descriptions made by Arthur Merschat were important in the lithologic and structural analysis of the site. Special thanks also to Ken Gillon and Nick Bozdog (NCGS) for their assistance in the mineralogical characterization of selected core samples.

The author wishes to acknowledge the U.S. Forest Service for their cooperation in this project and for providing access to suitable drill sites. Henry McNab (U.S. Forest Service) provided expertise and logistical support during the project, and his assistance is greatly appreciated.

The field work and drilling activities associated with this investigation were substantial and required the effort of many individuals, including Ray Milosh, Billy Casper, Jesse Martin, Chuck Pippin, Rick Bolich, Don Geddes, Shuying Wang, Andrew Pitner, Joju Abraham, and Landon Davidson of the NCDENR DWQ and Brad Huffman of the USGS. Finally, special thanks are extended to Melinda Chapman, Landon Davidson, Rick Bolich, Brett Laverty, Shuying Wang, and Ken Gillon for their review of the data interpretations and (or) manuscript. Their comments and suggestions greatly improved the report.

HYDROGEOLOGIC SETTING

The BCRS is located within the Blue Ridge physiographic province, a dynamic, rugged, mountainous landscape that has undergone continual evolution during various episodes of metamorphism, igneous intrusion, folding, faulting, and erosion throughout its billion-plus year history. Groundwater in this region occurs in complex hydrogeologic terranes that vary locally with local geology. The geology through which groundwater flows in these regions consists of (1) an unsaturated zone of soil (organic rich), alluvium, colluviums, and weathered bedrock; (2) a saturated zone of highly weathered (residuum and saprolite) bedrock; (3) a saturated zone of partially weathered bedrock that is a transition between weathered and unweathered rock; and (4) fractured crystalline bedrock. Relatively shallow alluvium is common in areas proximate to active or buried stream channels, and colluvium occurs in areas associated with debris fans and flows. Saprolite is typically clay-rich, soft, friable, and porous, and is derived from in-place weathering of parent rock; as such, it retains the fabric and fractures of the parent rock but with a much lower bulk density. Transition zone material consists of partially weathered, highly permeable bedrock. Interlayering of weathered and unweathered rock within the regolith is common depending on the composition and texture of the parent rocks from which they are derived.

Taken together, the regolith is comprised of layers of soil, alluvium, colluvium, saprolite, and transition zone material, and grain sizes range from clay to boulders, with porosities ranging from 35 to 55 percent (Heath, 1980). Because of its high porosity, the regolith is the storage reservoir for water to the underlying fractured bedrock flow system. Porosity decreases with depth in the regolith as weathering decreases (Stewart, 1962). Porosity of bedrock in the region ranges from about 1 to 3 percent. Most water bearing openings in bedrock are associated with joints, faults, and stress relief fractures rather than pores.

Chemical and mechanical weathering produces a regolith layer that varies in thickness from 0 to 150 feet in the North Carolina Piedmont and Mountains (Daniel and Dahlen, 2002). Many factors affect the weathering of parent rock, including climate, topographic setting, and rock composition, texture, structure, and degree of foliation. For example, feldspars and micas weather to produce clay-rich residuum and saprolite with high porosities and low hydraulic conductivities. The type and quality of weathering can affect the properties of groundwater flow and quality in both the shallow regolith system and the deeper fractured-flow system. As such, an understanding of the rock type, texture, and structure is important in evaluating groundwater occurrence, flow, and quality at a site.

Regional Geology

The state is divided into geologic belts with similar rock types and geologic history, but significant variability occurs at the local scale. The BCRS is located within the Blue Ridge Belt (NCGS, 1985), a terrain that consists of a complex mixture of metamorphosed sedimentary and igneous rocks that have been folded, fractured, faulted, and altered during multiple high temperature and pressure metamorphic events. Its major rock units occur as northeast trending belts, and its tectonically derived fractures tend to be oriented to the northeast and northwest. Hydrogeologic units in the Blue Ridge Belt include felsic gneiss, mafic gneiss, schist, quartzite, and phyllite (Daniel, 1989).

Bent Creek is underlain by complex, highly metamorphosed sedimentary and, to a lesser extent, mafic volcanic rocks of the Ashe Metamorphic Suite and Tallulah Falls Formation, and include mica schist, metagraywacke, paragneiss, and amphibolite (Hatcher, 1971; NCGS, 1985). These rocks are of late Proterozoic age and have been metamorphosed to sillimanite grade. The mica schists are derived from metamorphosed siltstones and shales and are medium- to coarse-grained, lepidoblastic, and composed mostly of quartz, feldspar, biotite, muscovite, and garnet. The metagraywackes are derived from metamorphosed muddy sandstones and are fine- to medium-grained, granoblastic, and composed mostly of quartz, feldspar, biotite, muscovite, garnet, epidote, and apatite. The paragneisses include biotite-muscovite gneiss and biotite gneiss that extend across a large portion of central Buncombe and northern Transylvania Counties (Hatcher, 1971). Other rocks include compositional and textural variations of these (for example, metasiltstone and metaconglomerate) and other minor, discontinuous bodies such as migmatite, pegmatite, and granofels.

The NCGS state geologic map (1:500,000 scale, 1985) places Bent Creek within a unit of muscovite-biotite gneiss (Zam) (fig. 5), and regional mapping by Daniel and Payne (1:500,000 scale, 1990) places Bent Creek within the quartzite (QTZ) hydrogeologic unit (fig. 6). However, site-scale mapping places BCRS in a strongly foliated mica schist setting with interlayered (scales from inches to feet), weakly foliated metagraywacke/gneiss and migmatite (1:12,000 scale, Merschat and Carter, 2002 (map in appendix 1a); W. Burton, written communication, July 25, 2008 (map in appendix 1b). A small number of amphibolite bodies also occur locally. Foliations mapped by Merschat and Carter (2002) tend to strike to the NE and are moderate to steeply NW or SE dipping (fig 7). Two generations of schistocity are present: a steeply-dipping S1 that is parallel to bedding and primary compositional layering (photos in figs. 8a and 8b), and a gently to moderately-dipping S2 (photos in figs. 9a and 9b) that is axial planar to locally recumbent map-scale folds that dominate the structural framework (Merschat and Carter, 2002). Joints measured by Merschat and Carter (2002) generally are steeply dipping with a NW strike (fig. 10), roughly perpendicular to the axes of local-scale folds. The nearest regional fault is the NE trending Brevard Fault about 8 miles to the southeast (fig. 5).

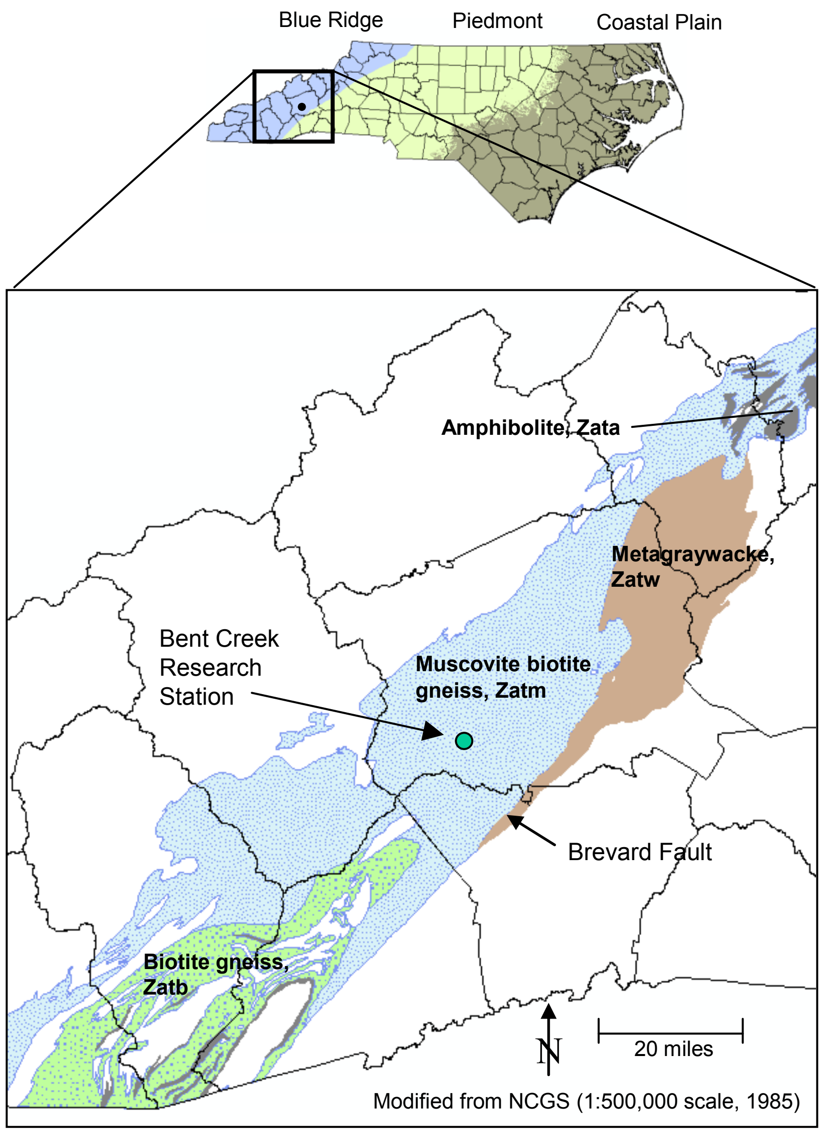

Figure. 5. Geologic formations in the Ashe Metamorphic Suite and Tallulah Falls Formation (modified from North Carolina Geological Survey, 1985) and physiographic provinces of North Carolina.

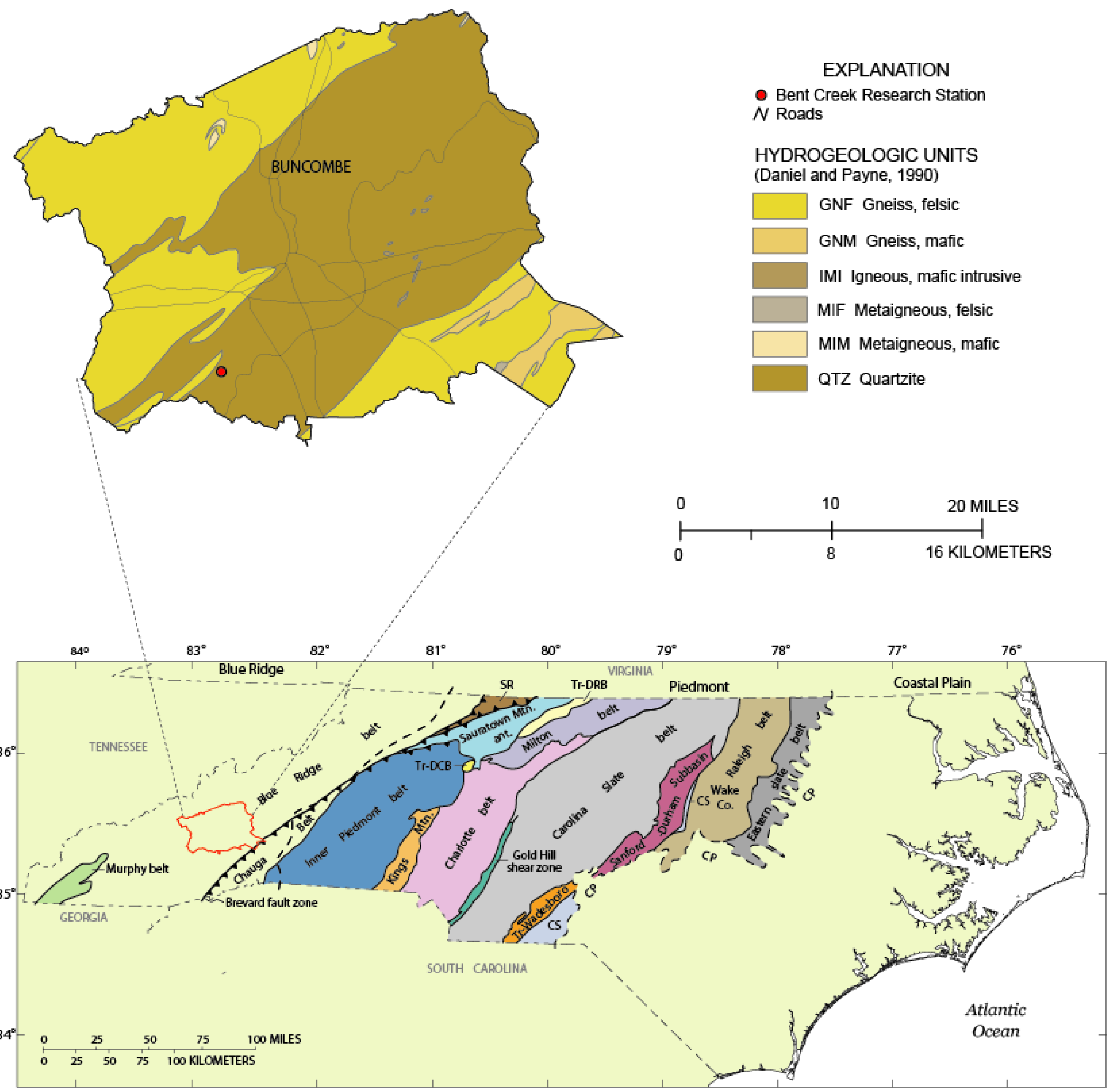

Figure. 6. Geologic belts in North Carolina (North Carolina Geological Survey, State map, 1:500,000 scale, 1985) and hydrogeologic units mapped by Daniel and Payne in Buncombe County (1990) (upper inset), as modified from Huffman and others, 2006.

Figure 7. Stereonet projection of poles to foliations, fold axes, crenulation axes and mineral lineations within the Bent Creek watershed, Asheville, North Carolina, modified from Merschat and Carter, 2002.

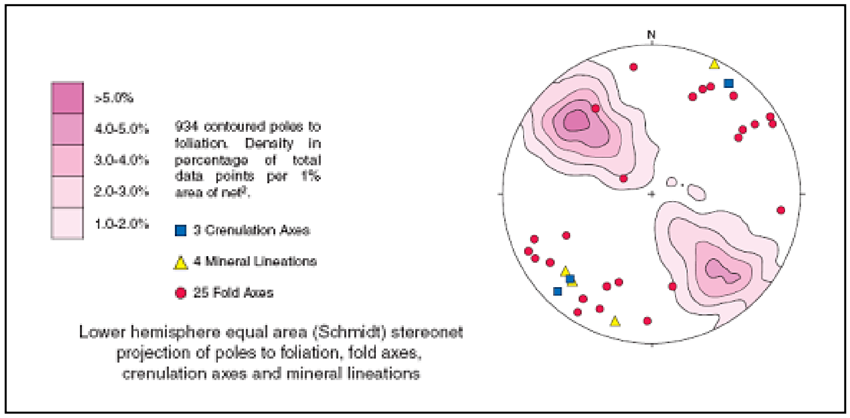

Figure 8A. Example of well developed, steeply NW-dipping S1 compositional layering in biotite gneiss/metagraywacke on Blue Ridge Parkway about two miles west of Bent Creek Research Station, North Carolina. W. Burton, written communication, July 25, 2008.

Figure 8B. Example of S1 schistocity (compositional layering) in mica schist (ms), in northwest part of the Bent Creek Research Station, North Carolina (just north of outcrop observation station BC-11 shown in appendix 1b), facing west. Well-defined layers reflect varying quartz content. W. Burton, written communication, July 25, 2008.

Figure 9A. Example of locally dominant, SE-dipping S2 schistocity showing iron-sulfide precipitation (above hammer), on Blue Ridge Parkway about two miles west of Bent Creek Research Station, North Carolina. Remnants of steeply-NW-dipping S1 compositional layering visible at lower left. W. Burton, written communication, July 25, 2008.

Photo by B. Burton, July 2008

Figure 9B. Example of medium- to fine-grained mica schist, S dipping S2 schistocity dominant foliation (strike at N83E, dipping 43 degrees), transposing N-dipping S1 compositional layering (strike at N87W, dipping at 50 degrees) to produce intersection lineation (at pen) on S2 surface, in northwest part of Bent Creek Research Station, North Carolina (outcrop observation station BC-4 shown in appendix 1b), facing west. W. Burton, written communication, July 25, 2008.

Photo by B. Burton, July 2008

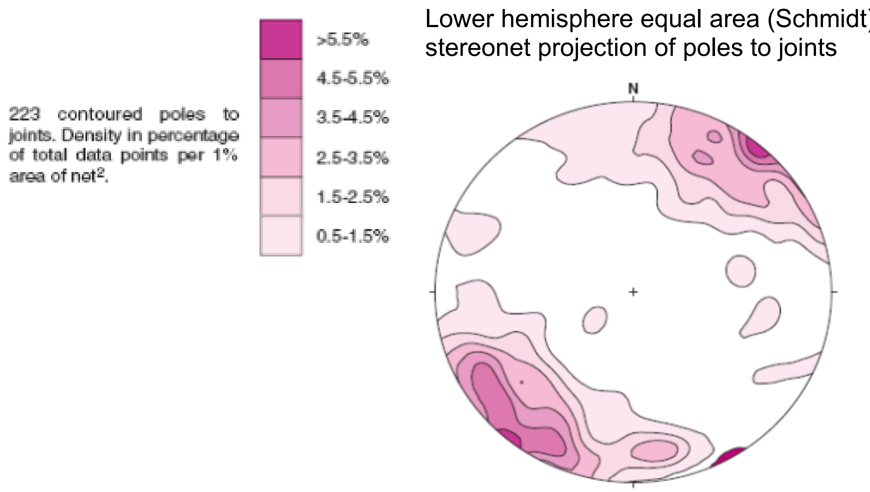

Figure 10. Stereonet projection of poles to joints within the Bent Creek basin, Asheville, North Carolina, Merschat and Carter, 2002.

Local Geology

The BCRS contains two dominant lithologies (minerals listed in order of increasing abundance): biotite (minor)-muscovite-garnet-quartz-plagioclase-chlorite schist (photos in figs. 8b, 9b, 11, 12, and 13a; table 1) and muscovite-biotite-quartz-plagioclase gneiss/metagraywacke (photos in figs. 8a, 11, 12, 13a, and 14; table 1). Interlayering (at scales ranging from inches to feet), compositional variation, and migmatization are common (photos in figs. 8b, 11, and 13a). Accessory minerals include garnet, sillimanite, and pyrrhotite. Both lithologies contain interspersed layers and veins of migmatite and (or) leucosome. Minor bodies of amphibolite occur locally. This description is consistent with mapping by Merschat and Carter (2002) and Burton (W. Burton, written communication, July 25, 2008) and with observations of seven rock cores.

Merschat and Carter mapped two dominant lithologies within the Boyd Branch sub-basin as part of their work in Bent Creek (1:12,000 scale): 1) a very light gray to greenish gray to medium gray, strongly-foliated, fine-grained, lepidoblastic to porphyroblastic quartz-chlorite-garnet-muscovite schist (Zas), with thicknesses ranging from less than an inch to several inches and commonly interlayered with sillimanite-garnet-chlorite-mica metasiltstone; and 2) a light gray to medium dark gray, non- to weakly-foliated, medium- to coarse-grained, granoblastic to lepidoblastic, locally migmatitic muscovite-biotite-potassium-feldspar-quartz-plagioclase metagraywacke (Zag), with thicknesses ranging from several inches to several feet. Their interpretation was based on observations of outcrops and two thin sections of rocks collected in the study area. Burton described the lithologic setting similarly (W. Burton, written communication, July 25, 2008) based on his field reconnaissance of the Boyd Branch study area, but referred to the metagraywacke as a gray biotite gneiss (bgn) and listed slightly different relative percentages of mineral compositions (appendix 1b). Burton also described a minor occurrence of black and white layered migmatite gneiss (photo in fig. 13b) that corresponds to Merschat and Carter's migmatitic metagraywacke. Minor bodies of amphibolite were noted in both surveys.

Eighty eight to 192 feet of rock core was recovered from each of 7 locations in BCRS (fig. 4) to augment information obtained from outcrop observations and the geologic map prepared by Merschat and Carter (2002). In describing these cores, three dominant lithologies were noted (A. Merschat, written communication, August 25, 2003): 1) a light gray to greenish gray to dark gray, migmatitic, fine- to coarse-grained, porphyroblastic to lepidoblastic chlorite-garnet-muscovite-biotite schist with variable composition, texture, and migmatite content; 2) a very light gray to medium gray, fine- to medium-grained, muscovite-biotite-feldspar-quartz gneiss, referred to as metagraywacke, with variable migmatite content; and 3) a very light gray to medium gray, medium- to coarse-grained, foliated- to weakly-foliated, granoblastic muscovite-biotite-quartz-plagioclase and potassium feldspar gneiss, referred to as migmatite. A hybrid of types 1 and 2 also was noted, as well as white to very light gray, coarse-grained leucocratic pegmatite or leucosome, dominated by quartz and potassium feldspar with biotite, muscovite, and garnet, referred to as leucosome/pegmatite. Other very minor lithologies observed in the cores included amphibolite, quartzite, calc-silicate, and trondhjemite.

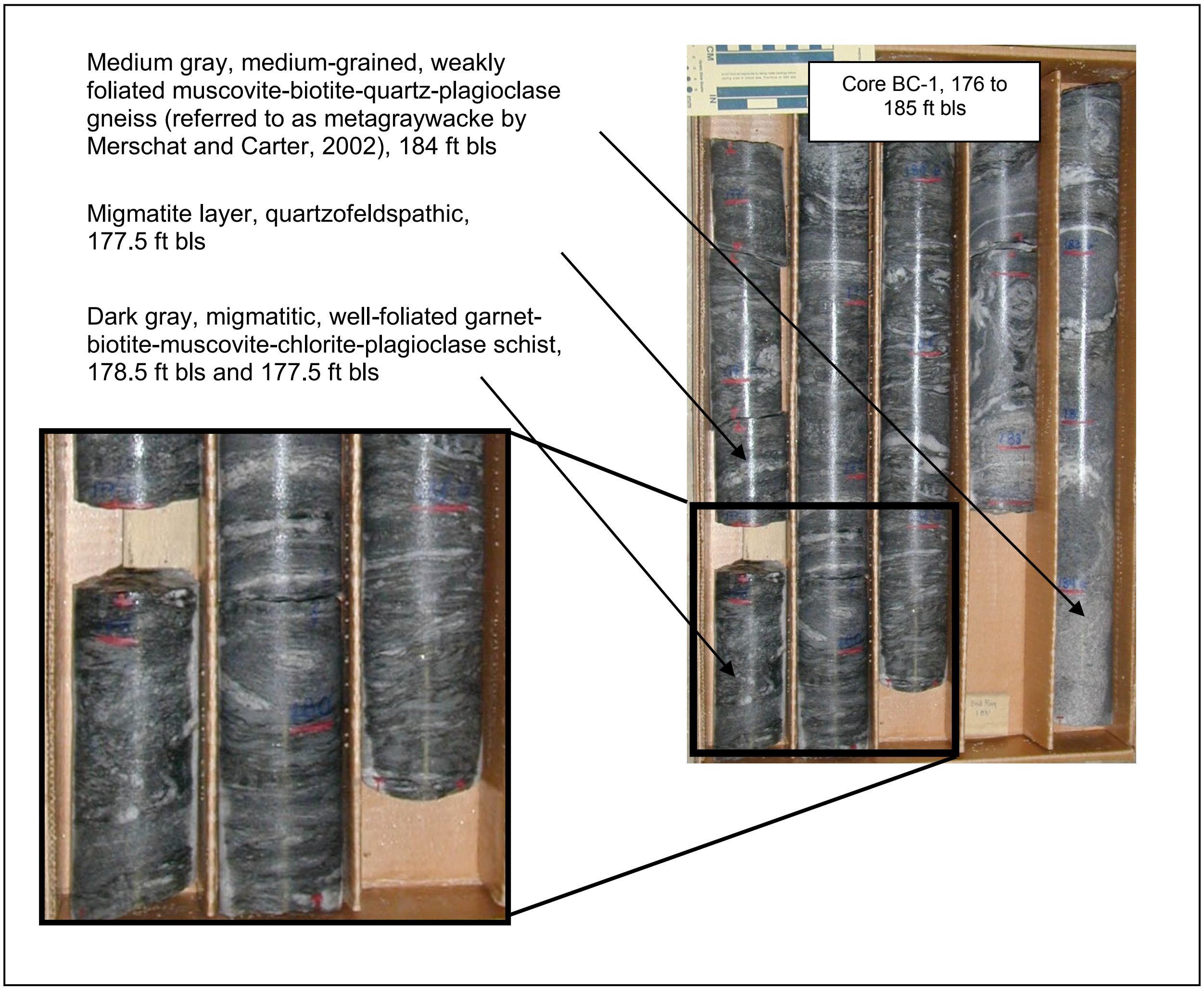

Figure. 11. Example of interlayered gneiss/metagraywacke, schist, and migmatite from rock sample at core site BC-1, Bent Creek Research Station, North Carolina.

Core site 1: very light to medium gray, medium- to coarse-grained, moderately to strongly foliated garnet-biotite-muscovite-quartzofeldspathic-chlorite SCHIST, interlayered with foliated leucosome

Core site 3: dark gray, fine- to medium-grained, weakly to moderately foliated garnet-chlorite-quartzofeldspathic GNEISS/METAGRAYWACKE, with very thin layers of leucosome

Core site 4: light to medium gray, medium to coarse grained, weakly foliated biotite-muscovite-garnet-quartzofeldspathic GNEISS/METAGRAYWACKE, with very thin layers of garnet-sillimanite-biotite-chlorite SCHIST

Core site 6: medium to dark gray, fine- to medium-grained, strongly foliated sillimanite, muscovite, biotite, quartzofeldspathic GNEISS/METAGRAYWACKE, with leucosome

Core site 7: medium to dark greenish gray, fine to medium grained, moderately foliated biotite, muscovite, biotite, quartzofeldspathic- SCHIST

Figure. 12. Samples from rock core sites BC-1, -3, -4, -6, and -7, with descriptions, Bent Creek Research Station, North Carolina.

Figure. 13A. Example of interlayered gneiss/metagraywacke, schist, and migmatite in outcrop located on Blue Ridge Parkway about two miles west of Bent Creek Research Station, North Carolina. W. Burton, written communication, July 25, 2008.

Figure. 13B. Isoclinally folded migmatitic gneiss, S-dipping (axial plane) folds (likely F2), looking west, at outcrop observation station BC-8 (shown in appendix 1b), Bent Creek Research Station, North Carolina. W. Burton, written communication, July 25, 2008.

Figure 14. Sample from rock core BC-1 showing biotite gneiss/metagraywacke and quartzofeldspathic leucosome, Bent Creek Research Station, North Carolina.

Dominant foliations within the study area are an S1, sub-inch to inches scale, compositional layering, generally parallel to foliation (photos in figs 8a, 8b, and 13a; table 2), and an S2, a later schistocity, most commonly seen developing within the mica schist (photos in figs. 9a and 9b; table 2) (W. Burton, written communication, July 25, 2008). The S2 foliation overprints S1 and is axial planar to F2 folds that fold S1 compositional layering. The S1 layering is typically NE-striking and steeply NW dipping (typically 50 to 80 degrees), but can be gently NW-dipping or overturned to steeply SE-dipping (about 70 to 90 degrees) by F2 folds. S2 schistocity is also NE-striking and typically moderately SE-dipping (typically 30 to 80 degrees). These observations are in agreement with those mapped by Merschat and Carter (2002), with rock cores, and with data obtained using an oriented optical televiewer in bedrock wells (appendix 2).

Table 1. Description of rock types common at Bent Creek Research Station, North Carolina, modified from Merschat and Carter, 2002 and A. Merschat, written communication, July 1, 2003.

Dominant rock types	Description[a]	Occurrence	Accessory minerals
Schist	Light gray to greenish gray to dark gray; strongly foliated; migmatitic; fine- to coarse-grained; quartz-biotite-sericite-chlorite-muscovite; variable composition, texture, and migmatization; thickness of layering ranges from millimeters to centimeters; migmatite may be interlayered or occur as lenses parallel to foliation	Interlayered with gneiss/metagraywacke rock, often at scales of a centimeter to meters	Sillimanite, garnet, pyrrhotite
Gneiss[b] / metagraywacke[c]	Light to medium gray; variably migmatitic; non to weakly foliated; fine- to medium-grained, muscovite-biotite-feldspar-plagioclase-quartz; thickness of layering ranges from millimeters to decimeters; occasional millimeter to centimeter thick micaceous layers create stripped pattern; migmatite may be interlayered or occur as lenses and knots parallel to foliation	Interlayered with schist rock, often at scales of about a centimeter to meters	Garnet, pyrrhotite

Minor rock types	Description[a]	Occurrence	Accessory minerals
Migmatite	White to very light to medium gray; non to weakly foliated; medium- to coarse-grained; muscovite-biotite-quartz-k feldspar-plagioclase feldspar; occurs in thin layers and lenses within other rock types (most commonly metagraywacke) at thicknesses ranging from millimeters to decimeters	Interlayered and (or) vein-like, derived from local melting during regional high-grade metamorphism	Pyrrhotite, chlorite, chalcopyrite
Leucosome	White to very light gray; coarse grained; muscovite-biotite-quartz-k feldspar; occurs in thin layers and lenses parallel to foliation within other rock types at thicknesses ranging from millimeters to decimeters; occasionally cross-cuts foliation; less biotite and muscovite than the migmatite listed above	Interlayered and (or) vein-like, derived from local melting during regional high-grade metamorphism	Pyrrhotite, chlorite, chalcopyrite
Amphibolite	Black to dark gray to greenish gray; non to strongly foliated; variably migmatitic; medium- to coarse-grained; varying mineral composition	Sparse, discontinuous bodies, possible interlayering	Pyrrhotite, chalcopyrite

[a] minerals listed in order of increasing abundance

[b] referred to as gneiss by B. Burton, written communication, July 25, 2008

[c] referred to as metagraywacke by Merschat and Carter, 2002

Table 2. Dominant foliations within the Bent Creek Research Station, as mapped by W. Burton (written communication, July 25, 2008) and foliation attributes in bedrock wells at Bent Creek Research Station, North Carolina.

S1 schistocity[a]

Rock type	Strike	Dip angle and dir	Location of outcrop
ms, mica schist	NE	32^o NW	BC-14, west of Boyd Branch
ms, mica schist	NE	73^o NW	BC-12, west of Boyd Branch
ms, mica schist	NE	57^o NW	BC-11, west of Boyd Branch
ms, mica schist	NE	53^o NW	BC-9, west of Boyd Branch
ms, mica schist	NE	78^o SE	BC-23, west of Boyd Branch
ms, mica schist	NE	73^o SE	BC-5, west of Boyd Branch
ms, mica schist	NE	83^o NW	east of Boyd Branch
ms, mica schist	NE	57^o NW	BC-1, east of Boyd Branch
ms, mica schist	NE	30^o NW	BC-18, east of Boyd Branch
ms, mica schist	NE	80^o NW	BC-16, east of Boyd Branch
ms, mica schist	NE	13^o NW	BC-15, east of Boyd Branch
bgn, biotite gneiss[c]	NE	88^o SE	BC-25, west of Boyd Branch
bgn, biotite gneiss[c]	NE	84^o SE	BC-24, west of Boyd Branch
bgn, biotite gneiss[c]	NE	42^o NW	BC-10, west of Boyd Branch
bgn, biotite gneiss[c]	NE	56^o NW	BC-13, west of Boyd Branch
bgn, biotite gneiss[c]	NE	78^o NW	BC-2, east of Boyd Branch
bgn, biotite gneiss[c]	NE	76^o NW	BC-20, east of Boyd Branch
bgn, biotite gneiss[c]	NE	42^o NW	BC-19, east of Boyd Branch
bgn, biotite gneiss[c]	E	38^o N	BC-38, east of Boyd Branch

S2 schistocity[b]

Rock type	Strike	Dip angle and dir	Location of outcrop
ms, mica schist	SE	28^o SW	BC-21, west of Boyd Branch
ms, mica schist	NE	78^o SE	BC-23, west of Boyd Branch
ms, mica schist	NE	60^o SE	BC-6, west of Boyd Branch
ms, mica schist	E	43^o S	BC-4, west of Boyd Branch
ms, mica schist	NE	12^o SE	BC-37, east of Boyd Branch

Monitor wells	Foliation attributes[d]	Rock type
BC-1D	NE strike, mod-steep dip to SE	interlayered, migmatitic ms-bgn
BC-2D	NE strike, mod-steep dip to SE	interlayered, migmatitic ms-bgn
BC-3D	NE strike, shallow-steep dip to NW & SE	interlayered, migmatitic bgn-ms
BC-4D	NE strike, shallow-steep dip to NW & SE	migmatitic ms
BC-5D	NE & N strike, moderate-steep dip to NE & N	interlayered, migmatitic bgn-ms
BC-7D	NE strike, moderate dip to NW & SE	interlayered, migmatitic ms-bgn

[a] associated with compositional layering; [b] overprints S1 & is axial planar to F2 folds that fold S1compositional layering;
[c] bgn also mapped as metagraywacke by Merschat and Carter, 2002; [d] determined from oriented OTV logs

Moderate to well-developed foliation was noted in the recovered rock from all seven core locations. Foliation strike orientations measured using optical televiewer data were to the NE in all bedrock wells and are moderate to steeply dipping (table 2; maps in appendix 1a and 1b). Grain sizes vary from fine to medium with lesser amounts of coarse material.

Mild, regional post-F2 warping may deform both S1 and S2, but no map-scale folds (F2 or later) could be identified. Map-scale lithologic contacts should follow the NE strikes of S1 foliation, with minor inflections caused by topography and F2 folding. Due to the complexity of lithologic interlayering, no map-scale contacts could be mapped with confidence in the study area (W. Burton, written communication, July 25, 2008). Faults or fracture zones were not observed in outcrops.

Jointing is not common in the study area but would be expected to increase in abundance as the predominant rock type increases from mica schist to biotite gneiss to migmatite gneiss to amphibolite. Twelve joints measured in the Boyd Branch sub-basin by Merschat and Carter (2002) are steeply SW or NE dipping (typically 50 to 80 degrees) and strike NW roughly perpendicular to the axes of their local-scale folds (appendix 1a). Based on observations of rock core, rock outcrops, and geophysical logs and optical televiewer data (appendix 2) rock partings in the study area generally are foliation parallel and moderately to steeply dipping.

Depth to bedrock ranged from 33 to 60 feet thick (median = 48 ft) in the seven cored locations, although outcrops occur sparsely along Boyd Branch, Bent Creek, and in other local areas of the basin (appendix 1a and 1b). The regolith is variably thick and consists of a thin mantle of organic-rich silty, sandy, clayey loam, highly weathered residuum and weathered saprolite, and a transition zone of partially weathered rock. The residuum generally is more weathered than saprolite and tends to lack textural fabric. The saprolite retains relict textures, structures, and fractures from its parent bedrock. Because of its granular and often clayey, silty character, the residuum-saprolite tends to be very porous and have a lower hydraulic conductivity than the underlying transition zone or bedrock fractures.

The transition zone is partially weathered material of varying grain sizes from silt to cobbles to large rock fragments, is very permeable, and retains the structure of its parent bedrock. It tends to weather unevenly, particularly in settings characterized by interlayered parent rocks, and often consists of inter-layered sequences of saprolite and (or) partially weathered and un-weathered bedrock. Alluvium and colluvium may occur locally, depending on the geomorphic setting.

The thickness of the soil, alluvium, colluvium, residuum, saprolite, and transition zone layers varied with location. Because of uneven weathering, a clear delineation between layers was not always apparent, and a subjective interpretation was made as necessary. Thicknesses of soil, saprolite, and transition zone material observed in the 7 BCRS cores are shown in the schematic in fig. 15.

Three types of weathering were noted in the study area: (1) an even grading from soil to residuum to saprolite to transition zone was noted at sites 2, 3, 4, and 6 (see example in photo of core BC-3, fig. 16); (2) soil/alluvium/colluvium grading directly to transition zone material (saprolite is nearly absent) at site 1 located in a low lying setting adjacent to the basin-draining third order Bent Creek (see example in photo of core BC-1, fig. 17); and (3) a repeating sequence of unweathered rock interlayered within intervals of saprolite and (or) transition zone material occurs at sites 5 and 7 (see example in photo of core BC-5, fig. 18)[1].

[1] The occurrence of interlayered sequences of unweathered and weathered bedrock has important implications for well design, particularly those associated with contaminant transport investigations, due to the potential for insufficient seating of surface casing material and (or) contaminant underflow through unanticipated, partially weathered, highly transmissive channels that can occur several feet beneath the surface of otherwise competent bedrock

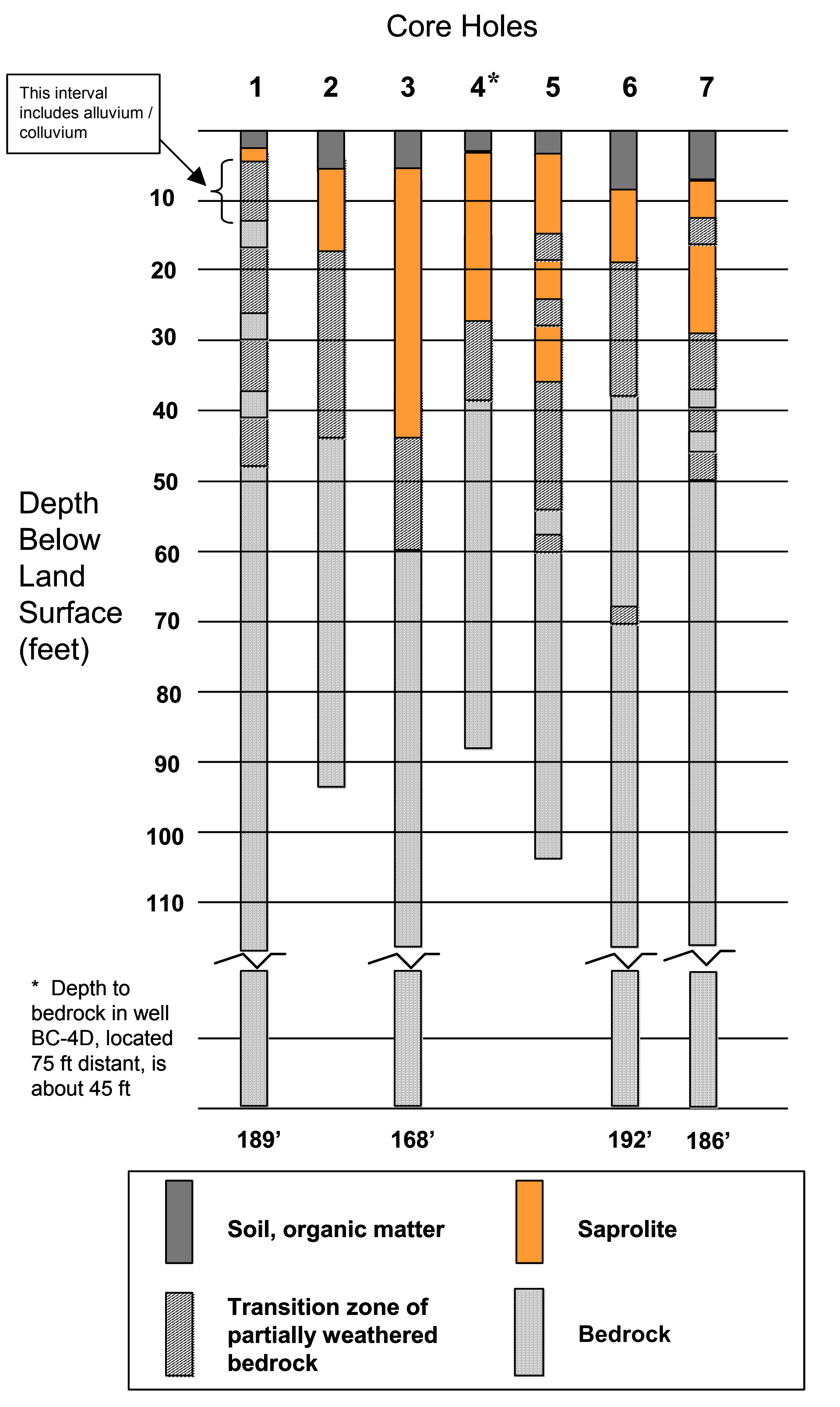

Figure 15. Near surface geology in seven cored locations at Bent Creek Research Station, North Carolina.

Figure. 16. Core recovery of regolith illustrating even, gradational weathering at BC-3, Bent Creek Research Station, North Carolina.

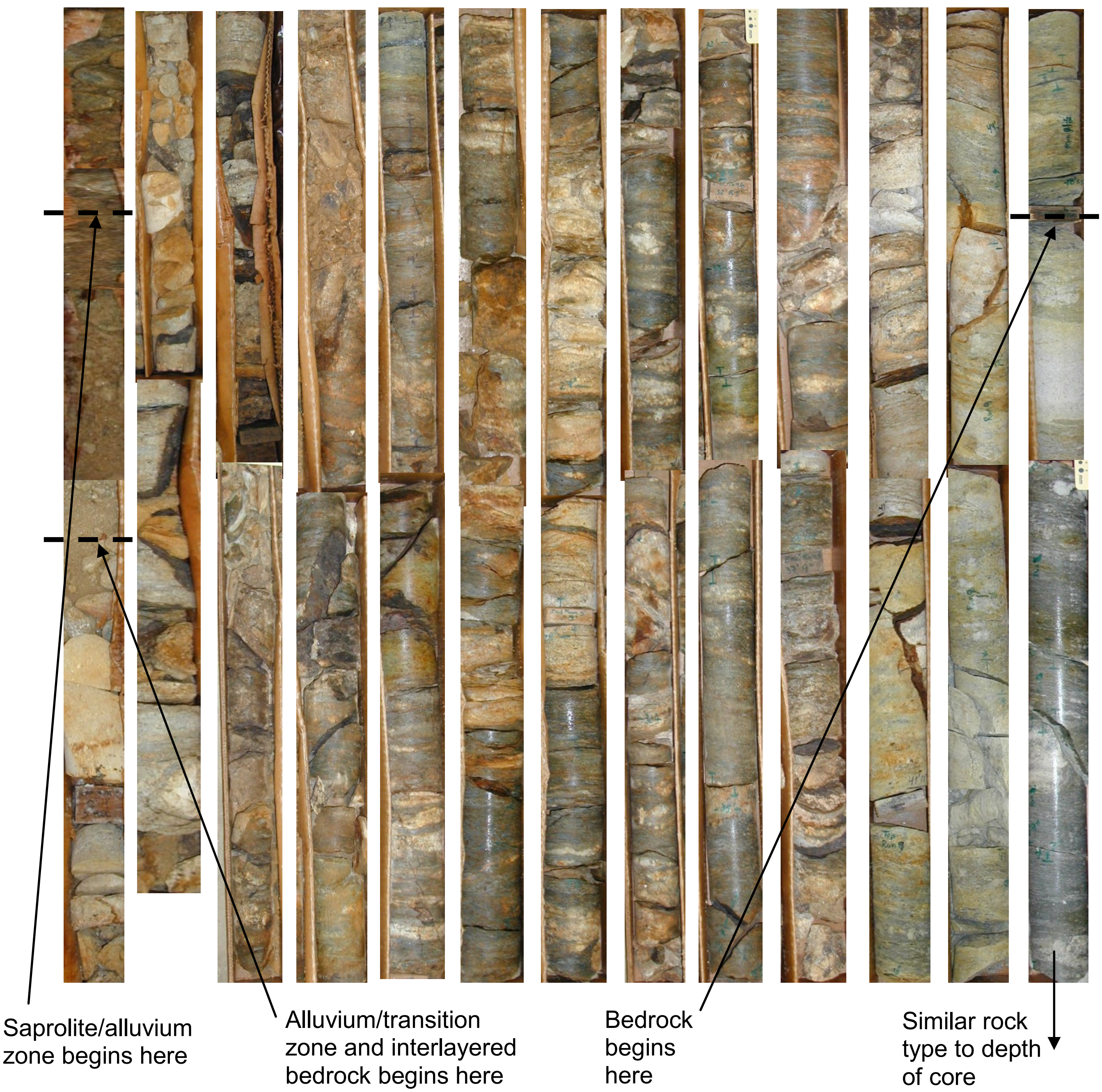

Figure. 17. Core recovery of regolith illustrating near absence of saprolite at low-lying site BC-1 adjacent to Bent Creek, Bent Creek Research Station, North Carolina.

Figure. 18. Core recovery of regolith illustrating interlayered transition zone at BC-5, Bent Creek Research Station, North Carolina.

Saprolite ranged from about 10 to 38 feet thick (median = 23 ft), except at the low-lying site BC-1 adjacent to Bent Creek, where long term scouring has resulted in a 2 feet thick layer (fig.17; table 3). Scouring also may have thinned the saprolite layer (12 feet thick) at site BC-2, another low-lying site adjacent to Boyd Branch near the base of the watershed. The thickness of the saprolite layer relative to the total regolith thickness was smallest at BC-1 (fig. 15; table 3). As observed in the cores, the uppermost saprolite consists primarily of reddish to golden brown, well-drained, fine- to coarse-loamy residuum, with varying clay, silt, and fine sand content. Deeper saprolite consists of orange-brown to medium brown to dark brown, clayey to sandy silt material that is weathered and retains the relict structure of its parent rock. Saprolite soils in BCRS are usually moderately to strongly acidic (4.5 to 6) and often are coated with iron oxides that produce a reddish complexion (soil maps, H. McNab, written communication, February 5, 2004). Alluvium/colluvium is present at sites BC-1 and -2. Five monitoring wells and eight piezometers were screened across saprolite to measure water level fluctuations and water quality in the upper regolith flow system.

Table 3. Summary of relative thicknesses of saprolite and transition zone material that comprise the regolith at seven core locations, Bent Creek Research Station, North Carolina.

	Core locations						
	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6	BC-7
thickness of saprolite, in feet	2	12	38	26	33	10	23
thickness of regolith[a], in feet	48	43	60	33	53	38	50
% of saprolite thickness to regolith thickness	**4**	**28**	**63**	**79**	**62**	**26**	**46**
thickness of transition zone, in feet	46	25	17	5	17	19	20
thickness of regolith[a], in feet	48	43	60	33	53	38	50
% of transition zone thickness to regolith thickness	**96**	**58**	**28**	**15**	**32**	**50**	**40**
depth to competent bedrock	48	43	60	45	53	38	50

[a] As defined here, regolith includes soil, saprolite, alluvium/colluvium, and transition zone material

A transition zone of partially weathered rock occurred at all sites and ranged in thickness from 5 to 46 feet (median of 19 ft) (table 3). The thickness of the transition zone relative to the total regolith thickness was greatest at sites BC-1 and -2 (figs. 15 and 17; table 3). The transition zone was defined as having both primary porosity (pores) and secondary porosity (rock partings). The transition zone material typically was overlain by an interval of dark brown sandy-clayey-silty saprolite.

Three of the 7 cores (BC-1, BC-5, and BC-7) were characterized by repeating sequences of transition zone material interlayered with saprolite and (or) unweathered rock (figs. 15 and 18). Uneven and interlayered weathering appeared to be associated with interlayering of parent rocks. Iron and manganese leachate stains were common on the fragments and fractures of most transition zone material, indicating oxidation-reduction reactions in the weathered, aerobic portion of the aquifer. Seven monitoring wells and 8 piezometers were screened across the transition zone to measure water level fluctuations and water quality at the base of the regolith flow system.

Depth to competent bedrock ranged from 33 to 60 feet (median of 48 ft) (fig. 15; table 3). Groundwater flow in bedrock occurs primarily within fractures and other rock openings. Based on core and OTV logs, fractures are mainly parallel to foliation and occur at moderate to steep angles. Low angle stress relief fractures that cross cut foliation occur less frequently. Where open, fractures often contained dissolution stains with either orangish brown to yellowish orange iron oxide (from the oxidation of iron sulfides, pyrrhotite, pyrite, or chalcopyrite) or black manganese oxide (from manganese-bearing minerals garnet, biotite, chlorite, or amphibole, for example). Staining occurred less frequently in the bedrock fractures than in the transition zone, particularly in anaerobic settings such as discharge areas. Seven open-hole monitoring wells were installed in bedrock to measure water level fluctuations and water quality in the deeper fractured rock groundwater flow system.

Surface Water

The Bent Creek watershed receives an average annual precipitation of 48 inches, distributed fairly evenly throughout the year (National Oceanic and Atmospheric Administration (NOAA) weather station 310724, located 2.5 miles from BCRS, fig. 3, 1949 to 2008, accessed from www.acis.sercc.com on July 2, 2009). Average monthly rainfall is highest in March (4.9 inches) and lowest in October (3.4 inches). Monthly rainfall amounts for the study period (fig. 19) were obtained from NOAA weather station 0246CA, about 1.2 miles N-NE of BCRS.

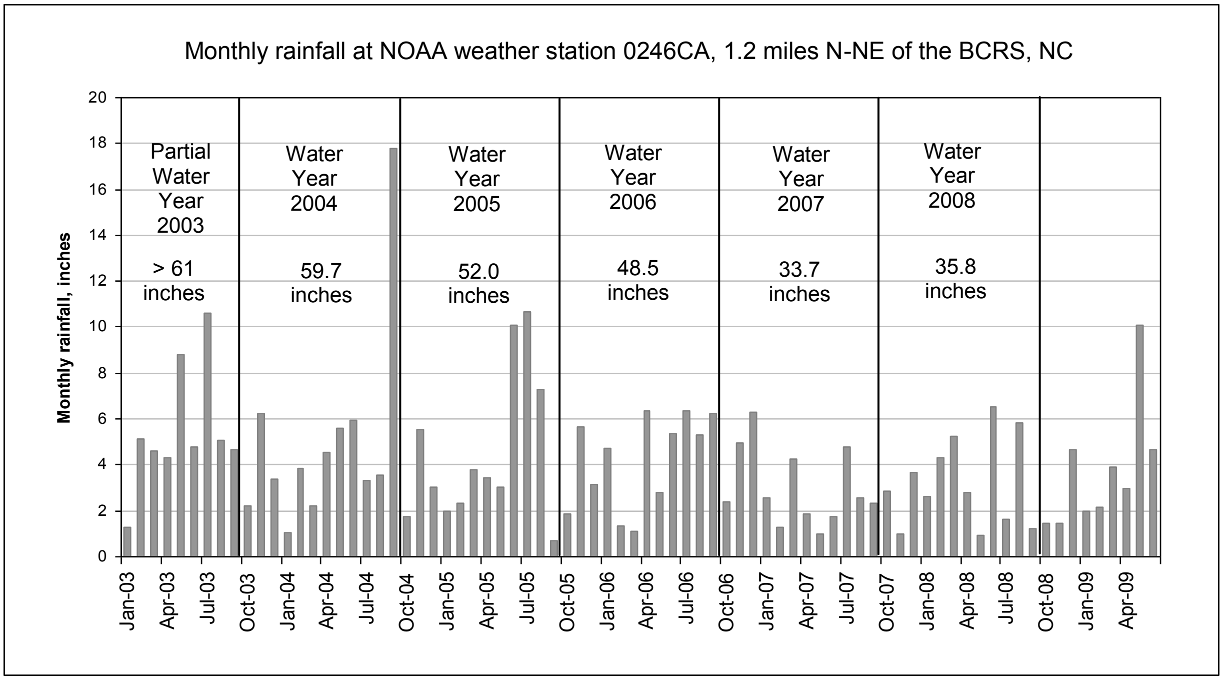

Figure 19. Monthly rainfall amounts at National Oceanic and Atmospheric Administration weather station 0246CA, 1.2 miles N-NE of the Bent Creek Research Station, North Carolina, January 2003 to June 2009.

A portion of this precipitation runs off the land surface into Bent Creek and its tributaries. The remainder evaporates, is transpired by plants and trees, or percolates downward through the unsaturated zone and recharges the groundwater system, eventually discharging to tributaries to Bent Creek or to Bent Creek itself. The surrounding ridgeline acts as the ground- and surface-water divide and therefore represents the basin boundary that separates flow in the Bent Creek basin from flow in other watersheds. A possible rare exception would be groundwater flowing through very deep fractures that are connected to an adjacent basin.

The 8.74 mi^2 Bent Creek watershed is drained by thirteen perennial 2^{nd} order streams that flow into Bent Creek (fig. 4). Bent Creek, a 3^{rd} order stream, flows into Lake Powhatan and 2.8 miles downstream where it empties into the French Broad River. Waters of the French Broad flow northwest, joining the Tennessee River, the Ohio River, and the Mississippi River, eventually emptying into the Gulf of Mexico.

From 2002 to 2008, annual mean stream flow in Bent Creek ranged from 6.7 cfs (2008) to 19.4 cfs (2005), based on discharge measurements at USGS gage 03447894 in Bent Creek just upstream of the French Broad River (figs. 3 and 20) (USGS Surface-Water Annual Statistics for the Nation, web accessed at http://waterdata.usgs.gov/nwis/sw on August 14, 2009). A peak flow of 3,000 cfs occurred in September 2004, corresponding to a period of intense rainfall associated with hurricanes Ivan and Frances. Highest flows tended to occur in April, and lowest flows tended to occur in August.

Mean streamflow for the period of record was estimated to be 15 cfs based on hydrograph separation computations using stream flow records and the USGS PART program (Rutledge, 1998). The program calculated baseflow in the pristine, largely undisturbed forest to be about 80 percent of this amount, or 12 cfs. When applied to the Bent Creek watershed drainage area of 8.7 mi^2, this corresponds to about 19 in/yr. Subtracting this amount from an estimate of annual mean precipitation of 48 inches gives an approximated value for direct runoff and evapotranspiration of 29 inches. These values are comparable to regional hydrologic budget estimates by Rutledge and Mesko (1996) (table 4). Wide variations are possible within a given region, area, or watershed since recharge is controlled by local precipitation, basin topography, land use (percentage of disturbed area), land cover, and soil type and thickness.

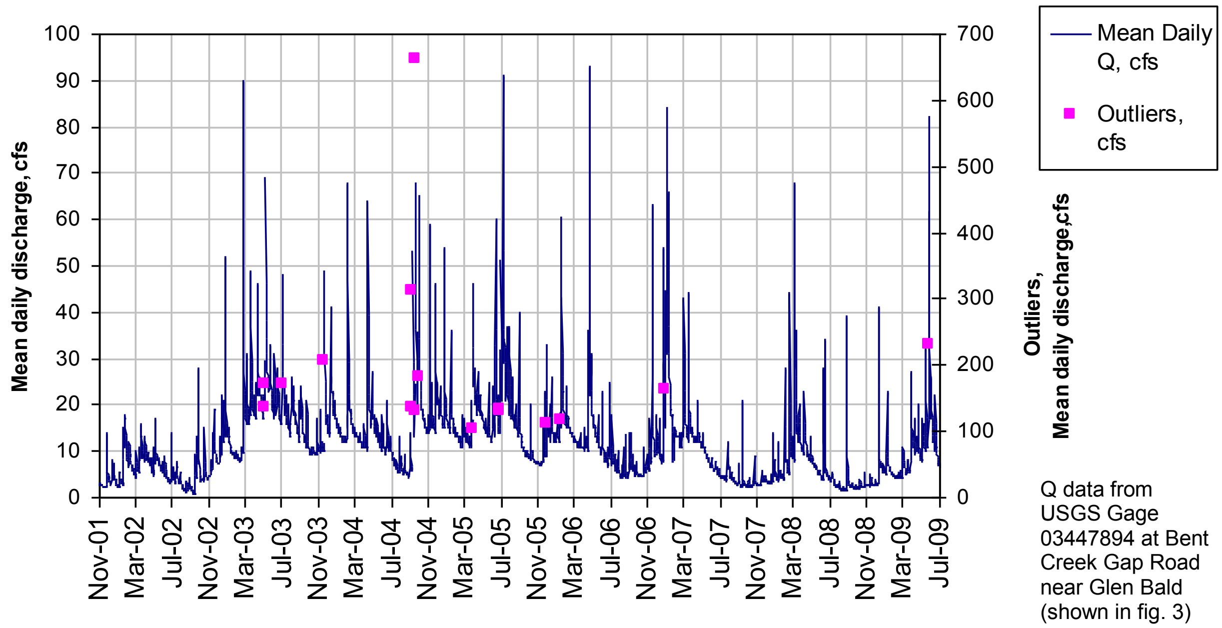

Figure. 20. Mean daily discharge (Q) in Bent Creek at U.S. Geological Survey gage 03447894, November 2001 to July 2009, modified from USGS stream records, accessed from webpage http://waterdata.usgs.gov/nc/nwis/ on August 14, 2009.

Table 4. Median values for hydrologic budget components in the Blue Ridge and Piedmont Provinces, in inches per year, as estimated using stream flow recession and baseflow analysis, from Rutledge and Mesko, 1996.

	Blue Ridge		Piedmont	
	Southern[a]	Northern[b]	Southern[a]	Northern[b]
Precipitation	58	43	48	44
Direct runoff	8	4	6	5
Evapotranspiration	25	27	32	29
Stream flow	38	16	18	15
Ground water recharge	33	12	12	10
Ground water discharge	29	11	11	8
no. of basins measured	17	10	15	13

[a] South of latitude 37
[b] North of latitude 37

Mean hourly stream flow in Boyd Branch ranged from 0.5 cfs to 56 cfs, with a median of 1.5 cfs, based on discharge measurements from March 1, 2004 to November 30, 2005 (fig. 21) at USGS gage 0344789265 in Boyd Branch at Bent Creek Road near Lake Powhatan (fig. 3). The daily mean peak flow of 56 cfs and the mean hourly instantaneous peak flow of 88 cfs occurred during September 2004, a period associated with heavy rainfall (17.8 inches in September) caused by hurricanes Ivan and

Frances. When applied to the Boyd Branch sub-basin watershed drainage area of 1.1 mi^2, the daily mean streamflow corresponds to 18.5 in/yr. The percentage of this amount represented by baseflow was not estimated because only 21 months of flow record were available.

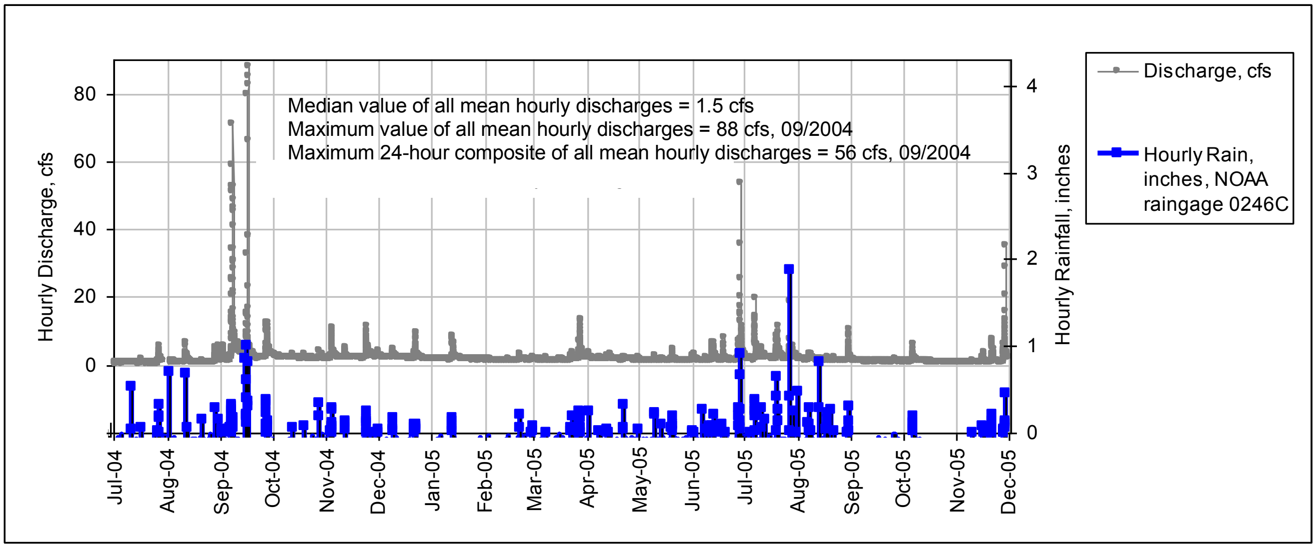

Figure. 21. Mean hourly discharges in Boyd Branch at U.S. Geological Survey gage 0344789265, Bent Creek Research Station, for period of record between July 2004 and December 2005, in relation to hourly rainfall.

Boyd Branch is moderately incised, ranging in channel depth from about 2 to 6 feet depending on location. Surface water depths range from about 0.5 to 2 ft, depending on recent rainfall events, location, and time of year. In a portion of its mid to lower reaches the channel is characterized by a relatively flat, wet, bog-like area of stream bifurcation prior to merging back into a single channel before its discharge to Bent Creek. Because Boyd Branch is only minimally incised in certain areas, a portion of groundwater underflows the stream and discharges directly to Bent Creek. As a result, this portion is not captured by discharge measurements in Boyd Branch, and the measured stream flow at the basin outlet very likely under-estimates the total amount of recharge and groundwater flow within the sub-basin.

Groundwater

Groundwater in the Piedmont-Mountains occurs within two geologic flow regimes: the regolith system and the underlying fractured crystalline bedrock. The regolith system is unconfined and made up of porous, weathered or partially weathered rock that acts as a storage reservoir for water to the underlying fractured bedrock system. The regolith system may be further subdivided into an upper layer (referred to as the upper regolith) of highly porous, low to moderately permeable, weathered residuum and saprolite, and a lower layer (referred to as the transition zone or lower regolith) of highly permeable, partially weathered rock that grades into unconsolidated bedrock. The regolith system also contains alluvium and colluvium, usually near surface in lower lying settings. The materials comprising the upper and lower regolith may be interlayered or even absent in some settings, and the degree of weathering may vary considerably across short distances. Because of its high porosity the regolith is the primary reservoir for groundwater storage and provides slow recharge to bedrock fractures (Heath, 1983, 1994). The fractured bedrock system underlies the regolith system, may be partially confined or unconfined, and is made up of very low porosity rock with partings that transmit water. Because the three flow zones usually have different matrix and hydraulic properties, groundwater is said to occur in a three-part system: upper regolith, lower regolith, and fractured bedrock.

Precipitation recharges the groundwater system at BCRS. A portion of the recharge moves laterally along shorter flow paths within the regolith and discharges to Boyd Branch or Bent Creek. Another portion moves laterally along somewhat longer flow paths within the regolith, underflows Boyd

Branch, and discharges to lower reaches of Boyd Branch or to Bent Creek. And a remaining portion moves downward into underlying bedrock fractures along longer flow paths and eventually discharges in lower reaches of Boyd Branch (as evidenced, for example, by artesian conditions at BC-2) or Bent Creek. Flow direction and travel time will depend in part on topography, thickness, continuity, and hydraulic properties of the regolith, and the number, size, orientation, and connectedness of bedrock fractures.

The three part groundwater system at BCRS (upper regolith, lower regolith, and fractured bedrock) was evaluated using data collected from 7 rock cores, 18 monitoring wells (grouped in 6 well clusters), and 15 regolith piezometers (grouped in 7 clusters). The well clusters were installed along a mile long NW-SE transect, from topographic highs to lows (figs. 4 and 22), and each cluster consists of an upper regolith (shallow, S), a lower regolith transition zone (intermediate, I), and a bedrock (deep, D) well. Upper regolith S wells have 15-foot screens across the water table within saprolite material (with the exception of BC-1S that is screened across alluvium/colluviums/transition zone material due to the absence of saprolite in this area). Lower regolith I wells have 15-foot screens across partially or highly weathered transition zone material just above competent bedrock. Bedrock D wells are open holes (with casing from land surface to the top of bedrock) in fractured bedrock to depths of 190 to 501 feet bls. Piezometers have 5-foot screens in the upper and lower regolith. Wire line coring, borehole geophysics, and downhole optical imaging were conducted at each well cluster location to understand and map lithology, structure, and fracture density. Borehole geophysical logs and direction-adjusted optical televiewer images are shown in appendix 2. Well construction details are shown in appendix 3. Groundwater levels were measured approximately monthly over a 5-year period between February 2003 and December 2008.

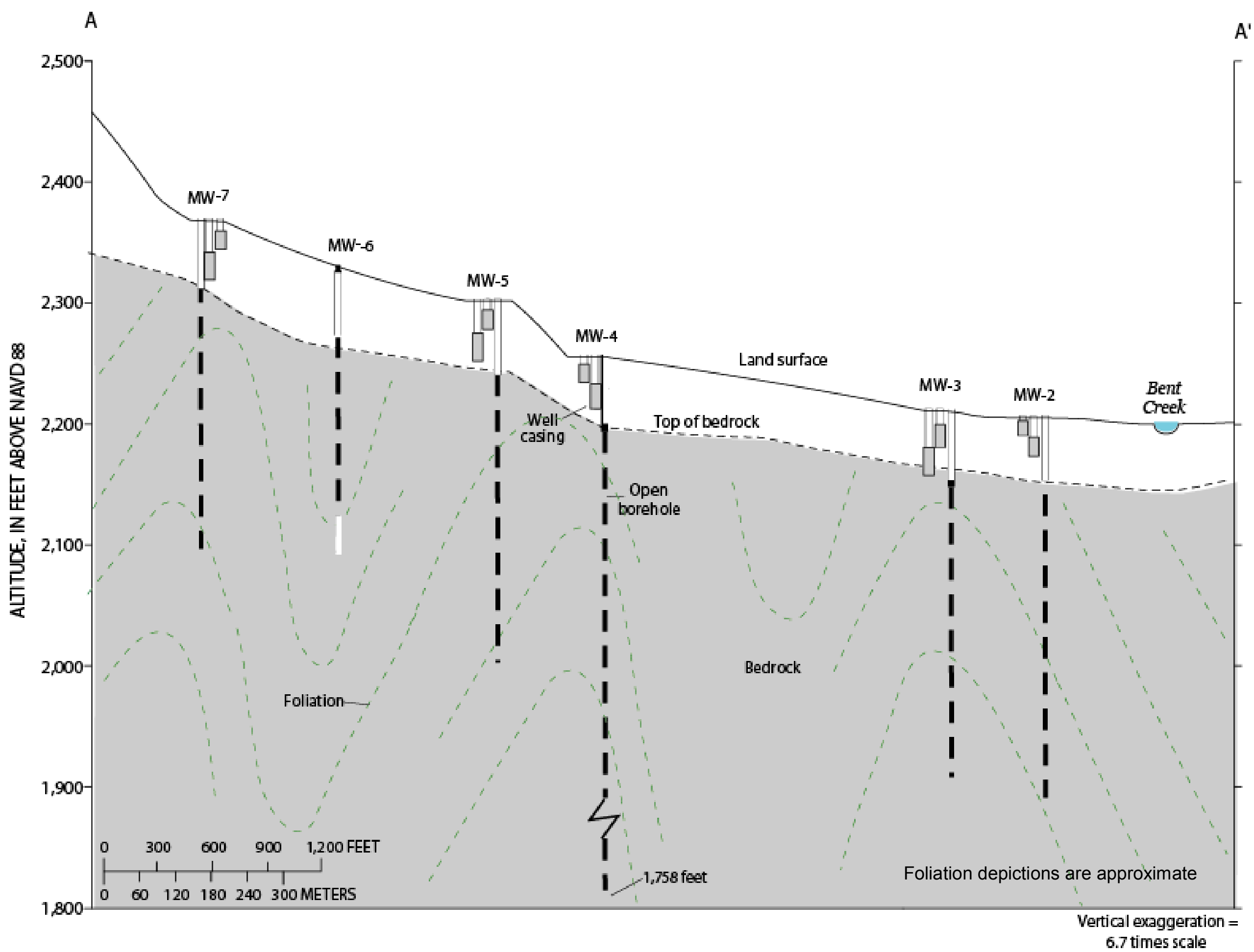

Figure 22. Generalized hydrogeologic cross-section along well transect at the Bent Creek Research Station, modified from Huffman and others, 2006.

Regolith Flow System

Two distinct flow zones – an upper and lower - occur within the regolith. The upper regolith flow system has a high porosity and variable permeability and consists of sandy, clayey, silty residuum-saprolite. The lower regolith flow system has variable porosity and high permeability[2] and consists of partially weathered transition zone material that varies in size from clay to boulder with both primary porosity (pore spaces) and secondary porosity (rock partings and veins). Directional, anisotropic hydraulic properties are common particularly in the lower regolith and are associated with relict foliations, fractures, contacts, and veins.

The thickness of the two-part regolith system measured in the study area ranged from 33 to 60 feet (median = 48 ft) (table 5; fig. 15). The upper system ranged from 2 to 38 feet thick (median = 23 ft), and the lower system ranged from 5 to 46 feet thick (median = 19 ft). Because of differential weathering, the thickness, composition, and permeability of the upper and lower flow systems vary with location, as does the depth to bedrock.

Groundwater generally follows topographic contours from higher to lower elevations. However, horizontal and vertical head gradients suggest that Bent Creek is a major influence on groundwater movement and discharge in the Boyd Branch sub-basin while Boyd Branch is, depending on location, a relatively minor influence. Bent Creek is a 3rd order stream and is the major drain for the larger watershed, while Boyd Branch is a 2nd order stream that drains the local sub-basin (fig. 4). Head gradients obtained from a May 24, 2005 synoptic round of water level measurements in 12 upper regolith wells/piezometers near P8 (figs. 4 and 23), a period of increasing evapotranspiration, suggest that most groundwater at this location flowed beneath Boyd Branch and south toward Bent Creek. The gradient from P8 to BC-4 is to the southwest, *away from* Boyd Branch. Boyd Branch does not incise deeply into the aquifer here (the elevation of the channel bottom is higher than the average water table elevation in this portion of the sub-basin). This observation suggests that only a small amount of groundwater near the top of the water table may be discharging into Boyd Branch in this location, with the remainder underflowing the stream[3]. Groundwater also underflowed a small intermittent tributary between P2 and P3 (figs. 4 and 23) during this measurement period; this is an area of recharge so unless the water table rises significantly, this is a losing reach of stream.

Areas of groundwater recharge and discharge were determined based on vertical head gradients and water temperature differences between clustered wells open to the upper regolith, lower regolith, and bedrock systems. As discussed in sections titled 'Seasonal and Storm-Induced Groundwater Level Fluctuations' and 'Vertical Head Gradients', recharge occurs in the areas of BC-7, -5, -4, and -3, and discharge occurs in the areas of BC-1, BC-2, and P8 (fig. 4). In recharge areas the vertical head gradients were downward from the upper regolith to the lower regolith to the bedrock system, resulting in a net downward flux of groundwater. In discharge areas the vertical head gradients were upward from lower portions of the flow system to upper portions of the flow system.

Properties

Lower regolith wells were associated with higher yields and permeability than upper regolith wells. This is due in large part to the more highly transmissive transition-zone material across which the lower regolith well is screened. At a given well cluster, the yield of the lower regolith well generally was higher by a factor of 3 to 10 than the yield of its clustered upper regolith well (table 5). In all, lower regolith wells yielded from 0.5 to 20 gpm (median = 5 gpm) and upper regolith wells yielded from 0.5 to 3 gpm (median = 1.5 gpm).

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[2] Well-developed transition zones tend to be highly transmissive and may significantly affect contaminant transport rates (Harned and Daniel, 1992).

[3] This is significant when considering issues of contaminant transport and groundwater flow direction in mountain watersheds, and demonstrates the importance of understanding several factors that may affect stream underflow, including: depth to water, depth of incised stream, underlying geology and thickness of regolith, size and shape of recharge boundaries, and relative topographic differences in both the sub-basin and larger watershed.

Displacement (slug) tests were conducted on regolith wells at sites 1, 2, 3, 4, 5, and 7 to evaluate hydraulic conductivity (K) in the immediate vicinity of the tested wells. The K values were about a half an order of magnitude higher in the lower regolith, transition zone wells than in the upper regolith, saprolite wells, consistent with the fact that the transition zone material is more permeable and transmissive. As shown in table 6, K values in shallow saprolite wells at BC-2S, -3S, -4S, -5S, and -7S ranged from 0.2 to 3 ft/day (median = 2 ft/day), and K values in transition zone wells BC-1S, -3I, -4I, -5I, and -7I ranged from 5 to 30 ft/day (median = 8 ft/day). A representative average K value for the upper regolith was about 1 ft/day and for the lower regolith was about 10 ft/day. Slug tests also were conducted in the bedrock well at three of these sites, however because the slug displacement volume was relatively minor in comparison to the total volume of water in the well bore, bedrock test results were considered to be accurate only to within an order of magnitude. In general, the K values in bedrock wells were over an order of magnitude lower than the K values in regolith wells.

The approximate velocity of groundwater was estimated using Darcy's Law, Q=KA dh/dl, where K = hydraulic conductivity and dh/dl = horizontal hydraulic gradient. Written another way and accounting for actual flow paths (porosity), velocity v = K dh/dl/porosity. The actual velocity will vary in different areas of the watershed and in different horizons of the groundwater flow system, and would be expected to be higher in steeper, upslope portions of the watershed, due to higher horizontal hydraulic gradients, than in flatter, lower lying areas, and higher in the lower regolith (transition zone) system, due to higher permeability and lower porosities, than in the upper regolith (saprolite) portion.

Porosity in the upper regolith system (mostly saprolite) was estimated to range from 0.25 to 0.7, with a representative value of about 0.5, based on published values for similar sediment types (Driscoll, 1986; Freeze and Cherry, 1979; and Roscoe Moss, 1990) (table 6). Porosity in the coarser grained lower regolith was estimated to be somewhat lower, with a range of 0.15 to 0.4, and a representative value of about 0.3. Hydraulic conductivity was estimated using slug test results and published values (Fetter, 2001) for similar sediment types (silt, clay, fine and coarse sand, and partially-weathered rock fragments of varying sizes, with the understanding that the percentage of coarser, less weathered rock fragments at BCRS generally increases with regolith depth).

Measured horizontal hydraulic gradients ranged from 0.01 to 0.05, but somewhat higher values are expected in upper, steeper portions of the watershed where water level data were not available (table 7). Applying these ranges of representative values to the equation v = K dh/dl/porosity, groundwater velocity v in the loamy sand, clay, and silt of the upper regolith is expected to be between about 0.01 and 1 ft/day, with a median of about 0.1 ft/day. Groundwater velocity v in the partially weathered, fragmented rock, cobbles, and silty sands of the lower regolith is expected to be between about 0.2 and 20 ft/day, with a median of about 2 ft/day. Actual velocities at any given location will depend on local geology, topographic setting, and rainfall activity (fluxes in the shape of the potentiometric surface). Vertical hydraulic gradients measured in regolith wells were comparable to the horizontal hydraulic gradients and ranged from 0.02 to 0.05 (table 7).

Storage

The volume of groundwater storage fluctuates with changes in rainfall, evapotranspiration, and groundwater withdrawals. Changes in land use/cover (impervious areas, for example) can increase rainfall runoff and thereby decrease recharge and storage, but these effects are minimal in the BCRS watershed. Storage increases during periods of rising water tables when precipitation is above normal (for example, during tropical storms in summer and autumn) and during periods of decreased evapotranspiration (during cooler periods in early spring and winter). As defined here, storage is the amount of water that would drain from the aquifer under the force of gravity, and is estimated by multiplying the volume of saturated regolith by the regolith porosity[4].

A very approximate estimate of total groundwater storage in the 1.1 mi^2 Boyd Branch basin was determined using observations of regolith thickness from seven rock cores and water levels in 27 regolith wells/piezometers measured from 2003 to 2008. For purposes of this estimation, it is assumed

[4] This measure is also referred to as specific yield for unconfined aquifers, which is the volume of water released from storage per unit surface area of the aquifer per unit decline in the water table (Freeze and Cherry, 1979).

Table 5. Geologic and hydrogeologic summary information obtained from rock coring and well testing at Bent Creek Research Station, North Carolina.

	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6	BC-7
Rock Type	ms-bgn; interlayered and migmatitic	ms-bgn; interlayered and migmatitic	bgn-ms; interlayered and migmatitic	ms-migmatite; interlayered	bgn-ms; interlayered and migmatitic	ms-bgn; interlayered and migmatitic	ms-bgn; interlayered and migmatitic
Regolith							
Thickness of saprolite, ft	2	12	38	26	33	10	23
Thickness of TZ, ft	46[e]	25[e]	17	5	17	19	20
Thickness of regolith, ft	48	43	60	45[d]	53	38	50
Type of weathering profile in regolith	very thin saprolite	even gradation	even gradation	even gradation	interlayered saprolite-TZ	even gradation	interlayered saprolite-TZ
Bedrock							
Depth to bedrock, ft bls	48	43	60	45	53	38	50
Foliated or non-foliated	foliated	foliated	foliated	foliated	foliated	foliated	foliated
Degree of foliation	moderate	moderate	moderate	moderate	moderate	moderate	moderate
Grainsize	fine to medium	medium	fine to medium	medium	medium	medium to fine	medium
Foliation strike direction	NE	NE	NE	NE	NE and N	nd	NE
Foliation dip azimuth and angle	SE / moderate-steep	SE / moderate-steep	NW and SE / shallow-moderate-steep	NW and SE / shallow-moderate-steep	W and NW / moderate-steep	nd	NW and SE / moderate
Well characteristics							
	primary[a] / secondary[b]	primary / secondary	primary / secondary	primary / secondary	primary / secondary	primary / secondary	primary / secondary
Number of fractures: 50 to 100 ft bls	0 / 3	0 / 7	1 / 2	0 / 7	0 / 6	nd	0 / 3
Number of fractures: 100 to 150 ft bls	0 / 13	0 / 2	0 / 3	2 / 0	0 / 2	nd	0 / 7
Number of fractures: 150 to 200 ft bls	1 / 7	0 / 3	0 / 7	0 / 3	0 / 3	nd	0 / 8
Number of fractures: 200 to 250 ft bls	0 / 2	0 / 2	0 / 3	0 / 2	0 / 5	nd	0 / 9
Number of fractures: 250 to 300 ft bls				0 / 0	0 / 9	nd	0 / 8
Number of fractures: 300 to 350 ft bls				0 / 2		nd	
Number of fractures per foot	0.006 / 0.15	0 / 0.06	0.004 / 0.06	0.004 / 0.03	0 / 0.10	nd	0 / 0.15
Predominant fracture strike direction	N (primary)	NE (secondary)	NE (primary)	NE (primary)	N-NE (secondary)	nd	NE (secondary)
Predominant fracture dip azimuth & angle	W / low	SE / moderate-steep	SE / moderate	NW / moderate	W-NW / moderate-steep	nd	SE and NW / mild-steep
Total well depth	221	300	300	501	300	190	285
Water level and flow characteristics							
Total water level fluctuation in bedrock well, February 2003 to August 2008	3.3	7.8	2.9	2.3	3.9	nd	1
Hydraulic conductivity (ft/d) and well yield (gpm) of upper regolith wells	30 / 5[c]	3 / 1	0.5 / 0.5	2 / 2	2 / 3	nd	0.2 / 1
Hydraulic conductivity (ft/d) and well yield (gpm) of lower regolith wells	10 / 15	5 / 5	5 / 2	nd / 20	10 / nd	nd	nd / 1
Hydraulic conductivity (ft/d) and well yield (gpm) of open hole bedrock wells	4 / 40	nd / 0.5	0.04 / < 0.5	0.2 / 6	nd / 1	nd / 3	nd / <0.5
Setting							
Proximity to stream/drainage	70 ft SE to Bent Creek (regolith wells); 170 ft SE to Bent Creek (bedrock well)	150 ft E to Boyd Br and 150 ft N to Boyd Branch; 600 ft E to Bent Creek	80 ft W to unnamed trib to Boyd Br; 130 ft NE to Boyd Br; 1100 ft SE to Bent Creek	190 ft NE to Boyd Branch; 2700 ft SE to Bent Creek	30 ft S to unnamed trib to Boyd Br; 250 ft to Boyd Branch; 3400 ft SE to Bent Creek	400 ft E to Boyd Branch; 4400 ft SE to Bent Creek	100 ft NE to Boyd Branch; 4600 ft SE to Bent Creek
Hydrologic setting	discharge	discharge	recharge	recharge	recharge	recharge	recharge

Notes: TZ, transition zone; ft bls, feet below land surface; nd, not determined; strikes and dips determined using optical televiewer data; [a]primary fractures are defined as open; [b]secondary fractures are defined as weathered but not open; [c]upper regolith well BC-1S is screened across alluvium; [d]depth to bedrock in core collected at site BC-4, about 75 ft distant, is ~ 45 ft; [e]contains alluvium/colluvium

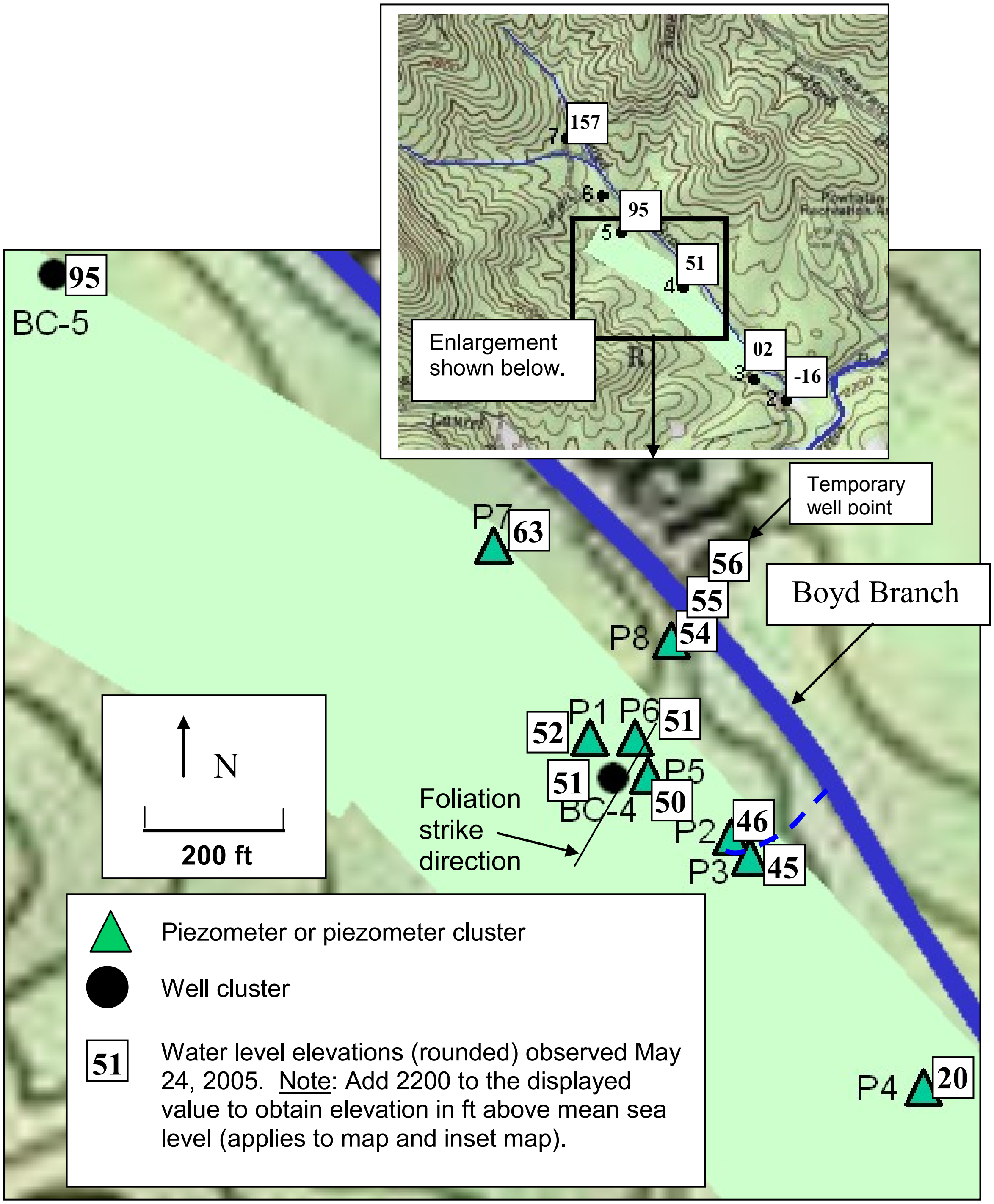

Figure 23. Observed water levels (rounded) on May 24, 2005, in vicinity of BC-4, Bent Creek Research Station, North Carolina.

that storage occurs primarily within the regolith. Regolith thickness ranged from 33 to 60 feet (median = 48 ft) in the 7 core locations and is expected to be somewhat thinner at higher elevations that were not cored; although regolith thickness will vary across the watershed, a uniform value of 35 feet was selected to represent average conditions. The average depth to water for the 27 observation wells/piezometers was 8 ft; depth to water is expected to be greater in higher elevations in the basin, so an average value of 12 feet was selected to represent average conditions. As referenced in table 8, the porosity of materials in the upper regolith (mostly saprolite) is estimated to range from about 0.3 to 0.6, with an average value of 0.5; the porosity of materials in the lower regolith (transition zone) is estimated to range from about 0.15 to 0.4, with an average value of 0.2. A representative value of 0.4 was selected as an average for the full, saturated thickness of the saturated regolith system across the basin. Using these values and assumptions, a typical value for total groundwater storage in the 1.1 mi^2 Boyd Branch basin during the climatic conditions and water level fluctuations that occurred between 2003 and 2008, was estimated to be about 1 to 3 billion gallons. However, not all of the water in storage may be released or mined, as hydraulic conductivities generally are much lower in clayey materials (such as at well cluster BC-7, for example) where porosities may be high.

Bedrock Flow System

In the deeper consolidated rock, groundwater flow is dependent upon the number, size, and aspect of fracture openings and their connectedness with fracture networks and the overlying regolith. This is because crystalline bedrock mostly lacks primary porosity[5]. The abundance and size of fractures are expected to decrease with depth, becoming less than 1 percent at depths below 750 feet due to lithostatic pressure (Daniel, 1989, 1992); this trend could not be evaluated in the study area because six of the seven bedrock wells were drilled to only 300 feet or less.

The bedrock flow system at BCRS is characterized by low porosity and permeability, with relatively few primary fractures[6] in rock cores and well bores. Well yields ranged from less than 0.5 to 40 gpm, with a median of 1 gpm (table 5) and an average of 7 gpm. These yields are far lower than the average yield of 16 to 22 gpm reported in similar hydrogeologic units in the mountain and piedmont regions of North Carolina (Daniel, 1989). This may be due to the fact that (1) foliation and fracture openings intercepted by bedrock wells at BCRS tend to be moderately to steeply dipping, and thus are less likely to intersect with and draw from the relatively few steeply dipping joints that are efficient conduits to abundant groundwater storage supplies from the regolith, and (2) mica schist is the dominant lithology underlying BCRS, and, conceptually, fewer rock openings may be expected in this rock type whose laminated cleavage planes can readily fold and deform without fracturing. Yields did not appear to be related to topographic setting. The K values obtained from slug tests in bedrock wells (4, 0.04, and 0.2 ft/day, for BC-1D, -3D, and -4D, respectively, with a median of 0.2 ft/day) were lower than the K values in regolith wells by over an order of magnitude.

Only 6 primary fractures were observed in the six bedrock wells using optical televiewer images and borehole geophysical logs (two in well BC-4D, and one each in wells BC-1D and -3D) (table 5 and appendix 2). The low number of primary fractures observed is consistent with conditions in a watershed underlain by mica rich schist whose laminated cleavage planes can readily fold and deform without fracturing. Of the six bedrock wells tested for ambient flow through the open borehole using a heat pulse flowmeter, only two had measurable readings (appendix 2); an ambient inflow of 0.1 gpm was observed in BC-2D at 53 ft, and an ambient outflow of 0.01 gpm was observed in BC-3D at 60 ft. It is possible that these very low flows were associated with well construction anomalies and not the natural formation because they occurred at the interface between the surface casing and bedrock, a position commonly associated with potential leakage to or from the regolith.

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[5] Porosity in fractured bedrock typically ranges from 1 to 10 percent (Freeze and Cherry, 1979), with lower values being far more common.

[6] Primary fractures are defined here as open and significant.

Table 6. Estimated aquifer properties in the regolith flow system, Bent Creek Research Station, North Carolina.

Porosity

Soil type	Published[a] porosity, n, in %	Estimated regolith porosity, n, in %
clay	40 to 70	
silt	35 to 50	
sand	25 to 50	40[b]
sand and gravel	15 to 35	
gravel	20 to 40	

Selected representative porosity = 0.5 (saprolite)

Selected representative porosity = 0.3 (TZ)

Hydraulic Conductivity

Well	Method used to estimate hydraulic conductivity	Hydraulic conductivity, K, in feet/day
BC-2S (Saprolite)	slug test	3
BC-3S (Saprolite)	slug test	0.5
BC-4S (Saprolite)	slug test	2
BC-5S (Saprolite)	slug test	2
BC-7S (Saprolite)	slug test	0.2
BC-1S (TZ)	slug test	30
BC-1I (TZ)	slug test	10
BC-2I (TZ)	slug test	5
BC-3I (TZ)	slug test	5
BC-5I (TZ)	slug test	10

Published value for soil types	Published[c] hydraulic conductivity, K, values in feet/day	
silt, sandy silts, clayey sands[d]	0.003 to 0.3	
silty sands, fine sands[d]	0.3 to 3	3[b]
well-sorted gravel[e]	30 to 3000	
Aquifer test results in regolith[f]	median K of 7 analyses	14

Selected representative K = 1 (saprolite)

Selected representative K = 10 (TZ)

TZ, transition zone

[a] Driscoll (1986), Freeze and Cherry (1979), and Roscoe Moss (1990)

[b] Chosen Representative value for study area, based on soil types and associated published values

[c] Fetter, C.W., Applied Hydrogeology, 2001, Prentis Hall, Inc., p.85.

[d] Soil types that make up upper regolith (saprolite) in study area

[d, e] Soil types that make up lower regolith (transition zone) in study area

[f] From 72-hour aquifer test conducted October 2004: median transmissivity ~ 640 ft2/day, with a saturated thickness ~ 45 ft

Table 7. Horizontal and vertical hydraulic gradients, Bent Creek Research Station, North Carolina.

Locations used in gradient observation	head difference	distance	horizontal hydraulic gradient
P7 to P4	45 ft	1095 ft	0.04
P4 to BC-3	17 ft	1070 ft	0.02
BC-3 to BC-2	18 ft	785 ft	0.02
P8 to BC-4	2 ft	222 ft	0.01
BC-7 to P7	93 ft	1800 ft	0.05

Locations used in gradient observation	head difference	distance	vertical hydraulic gradient
PC-3S to BC-3I	0.4 ft	20 ft	0.02
BC-4S to BC-4I	0.5 ft	18 ft	0.03
BC-5S to BC-5I	0.5 ft	23 ft	0.02
BC-7S to BC-7I	0.7 ft	20 ft	0.04
BC-1S to BC-1I	0.2 ft	13 ft	0.02
P2S to P2I	2 ft	37 ft	0.05

The existence of at least one primary fracture in the bedrock well bore generally was a good indicator that the well would produce significantly higher yields than wells without a primary fracture. For example, the two highest yielding wells, BC-1D (yield = 40 gpm) and BC-4D (yield = 6 gpm), have one primary and 25 secondary fractures, and two primary and 14 secondary fractures, respectively. The three wells that lack a primary fracture, BC-2D, -5D, and -7D, had yields of only 0.5, 1, and less than 0.5 gpm, respectively.

The number of observed secondary fractures was not predictive of relative bedrock well yield. For example, low yielding wells, BC-5D (yield = 1 gpm) and BC-7D (less than 0.5 gpm), were associated with the highest number of secondary fractures (25 and 35, respectively)(table 5). Similarly, the number of fractures per foot was not predictive of relative bedrock well yield (table 5).

Based on borehole geophysical and heat pulse flowmeter data, a good qualitative predictor of elevated well yield (defined here as 6 gpm or higher) was a combination of primary fracture(s) and a sharp caliper increase at a given depth. The highest yielding BCRS well, BC-1D (40 gpm), has both a primary fracture and a sharp caliper increase at 140 feet (appendix 2 and table 5). The second highest yielding well, BC-4D (6 gpm), has two primary fractures and a sharp caliper increase at 110 ft. In both cases flowmeter testing showed an increased flow rate at these depths. On the other hand, wells with only one of the two predictive features (for example BC-3D and BC-5D) had low yields (table 5).

Regolith thickness[7] was not predictive of relative bedrock well yield (table 5). For example, well cluster BC-3 had the thickest observed regolith (60 ft) of all six well cluster locations but the lowest bedrock well yield (less than 0.5 gpm). And well cluster BC-4 had the thinnest regolith (33 ft) of all six locations but the second highest bedrock well yield at 6 gpm. Factors affecting well yield include fracture size, density, and connectedness to overlying storage. Factors affecting long-term sustainability of this yield include (1) long-term rainfall and drought patterns, (2) regolith thickness, porosity, and permeability in upslope areas that recharge the well, (3) withdrawals from interconnected bedrock wells, and (4) withdrawals from wells in upslope recharge areas.

[7] Regolith thickness was determined from rock core collected from 30 to 70 feet away from the bedrock well, and aquifer characteristics may vary significantly in relatively short distances in fractured rock terrains.

Seasonal and Storm-Induced Groundwater Level Fluctuations

Water levels were measured monthly from February 2003 to August 2008 in six well clusters open to the upper regolith, lower regolith, and bedrock flow zones to observe seasonal changes and horizontal and vertical head gradients. Water levels also were measured hourly for several months at two representative well clusters (BC-7 in a recharge setting and BC-2 in a discharge setting), and at selected intervals at four other well clusters following rain events, to observe the response to storm events. Hourly rainfall data were obtained from NOAA gage 0246CA located 1.2 miles N-NE of BCRS.

The water table was about 2 to 15 feet bls during the study period depending on topographic setting, rainfall, and season (table 7 and fig. 24). Noted exceptions to this were well BC-2D, a flowing, artesian, open hole bedrock well in a discharge area with a water level about 1 to 9 feet *above* land surface, and well BC-6D, a midslope open hole bedrock well on a topographic rise a relatively distant 300 feet from Boyd Branch with a water level of 31 to 33 feet bls. The water table was closer to land surface in lower elevations of the basin (sites 1, 2, and 3, for example) than in higher elevations (site 7, for example) (fig. 24).

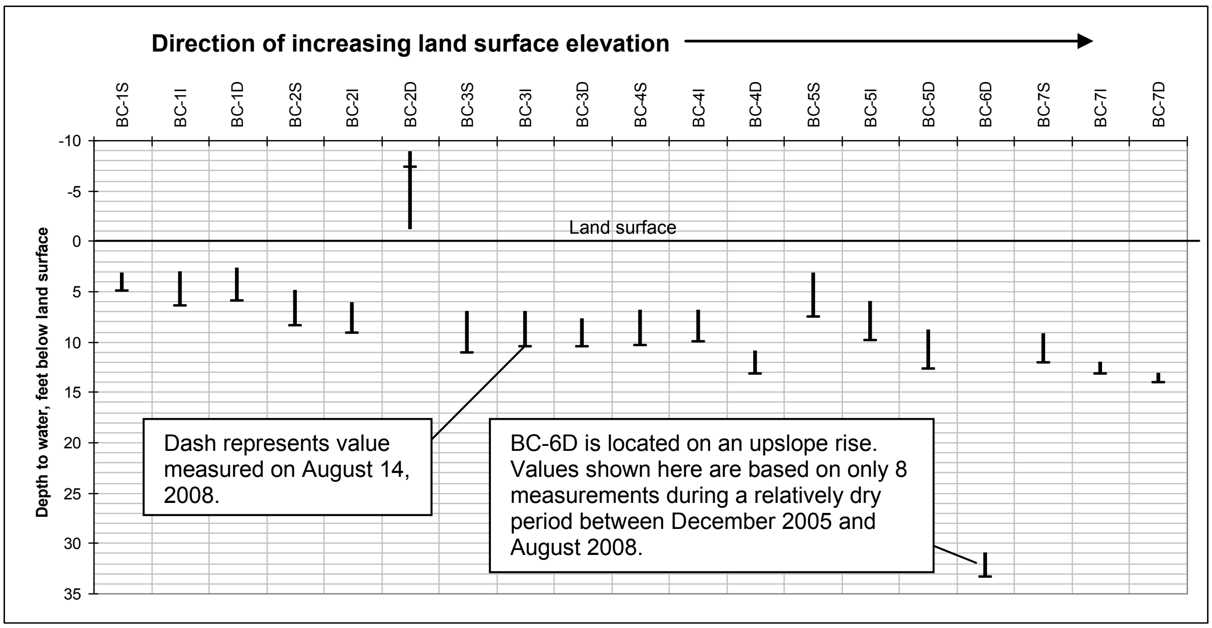


Figure. 24. Maximum and minimum water levels (in feet below land surface) as measured monthly between 2003 and 2008, and depth to water (shown as horizontal dash) measured on August 14, 2008, Bent Creek Research Station, North Carolina.

Most wells fluctuated 1 to 2 ft per year in response to seasonal fluctuations in precipitation and evapotranspiration, and water levels in the three parts of the groundwater system (upper regolith, lower regolith, and bedrock) followed similar patterns of fluctuation (figs. 25A to 25F)[8]. Water levels generally declined during late spring and summer months when soil moisture deficits tend to be high and evapotranspiration rates tend to be higher than rainfall, with the lowest levels observed in late summer and highest levels in late winter (figs. 25A to 25F).

Water level fluctuations usually were greater in regolith wells than in bedrock wells (figs. 25A to 25F and tables 8 and 9), due in part to the more immediate and direct response of regolith wells to rainfall recharge and due to the fact that water tended to be under at least some pressure in the semi-confined bedrock system. Water levels declined about 2 to 3 ft during the measurement period, with highs occurring in May 2003 (a year in which some areas of the State received over 50 percent higher rainfall than normal) and lows occurring in August 2008 (figs 25A to 25F), a year characterized by

[8] The fluctuation measured at a well is dependent upon the hydrogeologic setting, climate, and time of measurement.

regional drought conditions and historically low stream flows (USGS website accessed January 12, 2009; http://nc.water.usgs.gov/drought/).

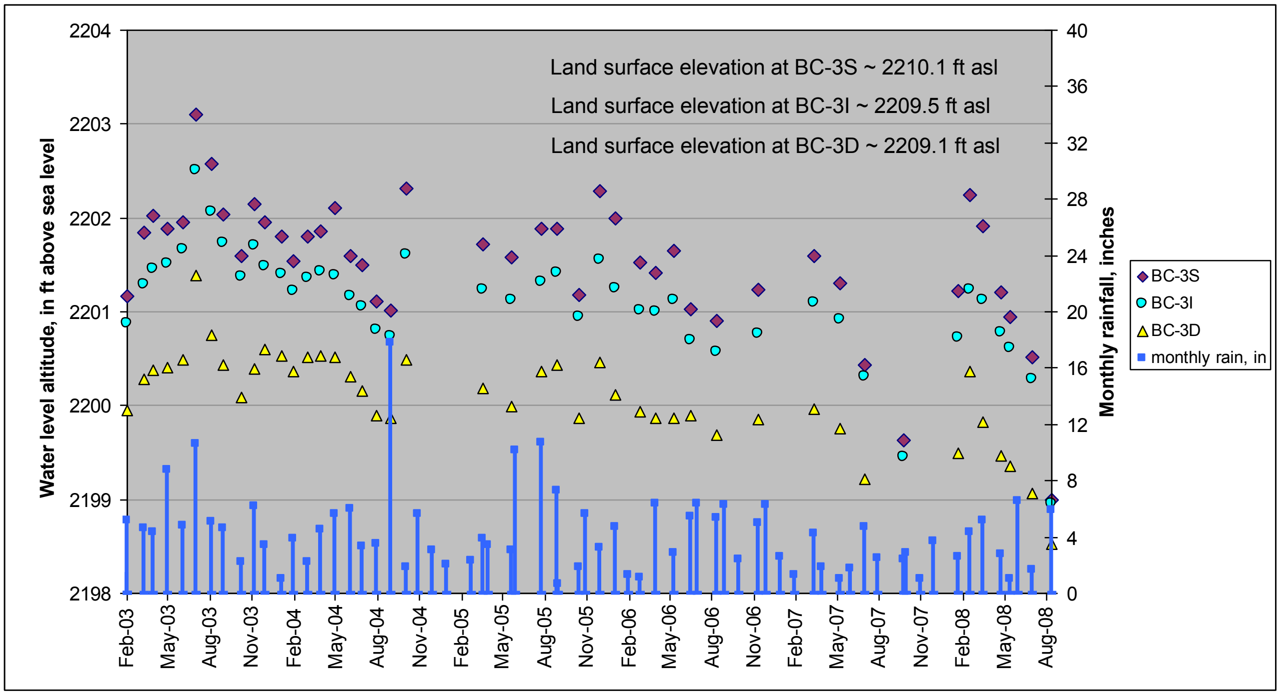


Figure 25A. Monthly water level measurements at cluster wells at site BC-3, a recharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

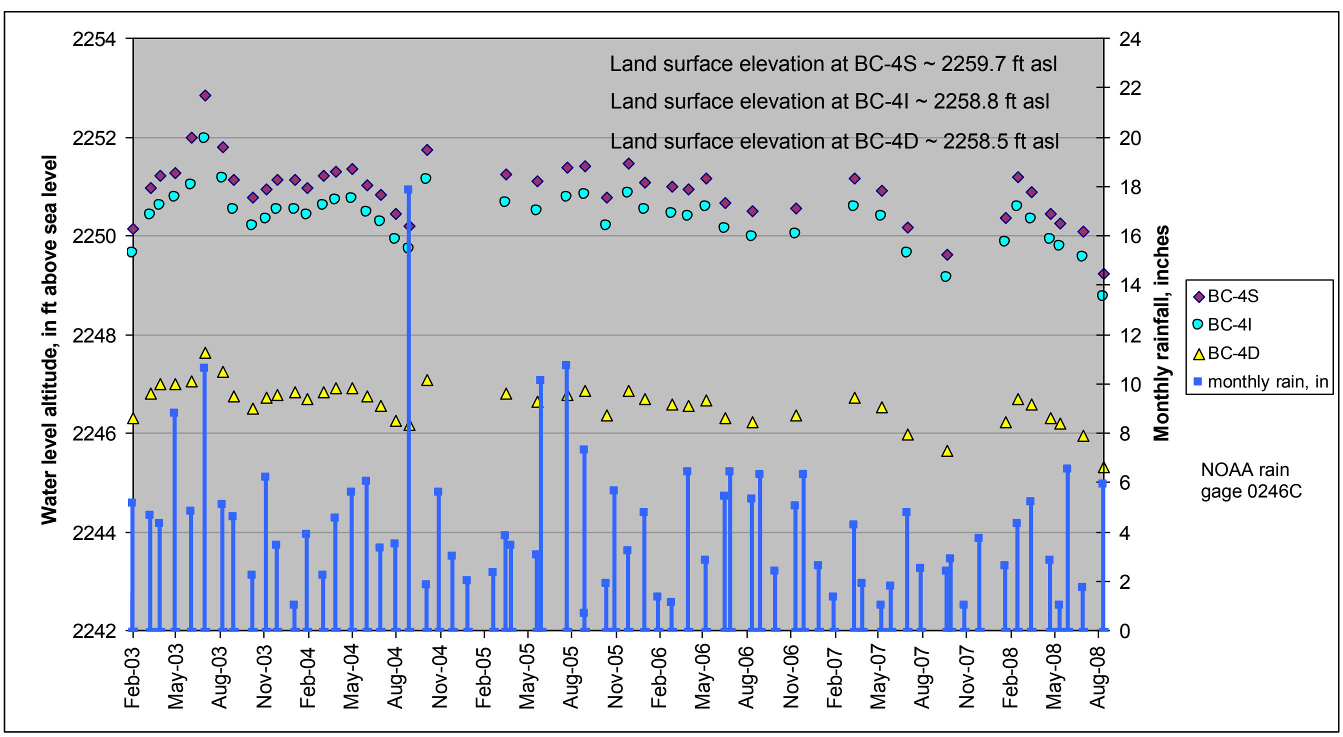


Figure 25B. Monthly water level measurements at cluster wells at site BC-4, a recharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

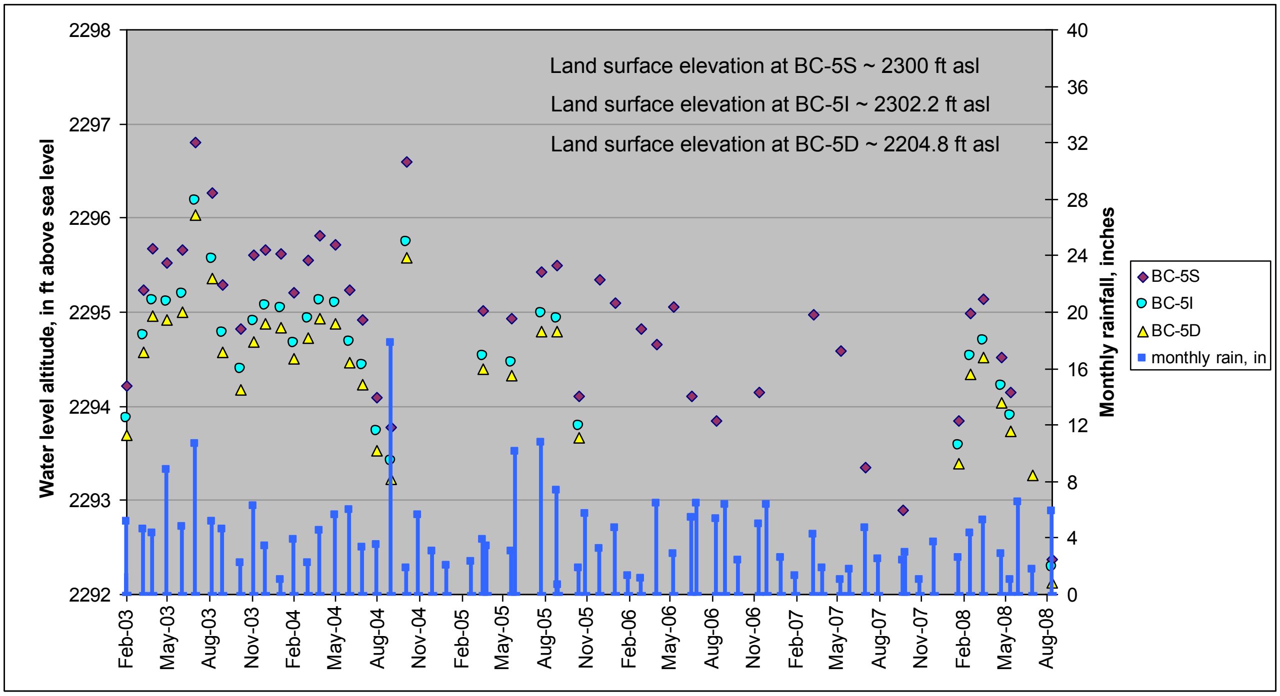


Figure 25C. Monthly water level measurements at cluster wells at site BC-5, a recharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

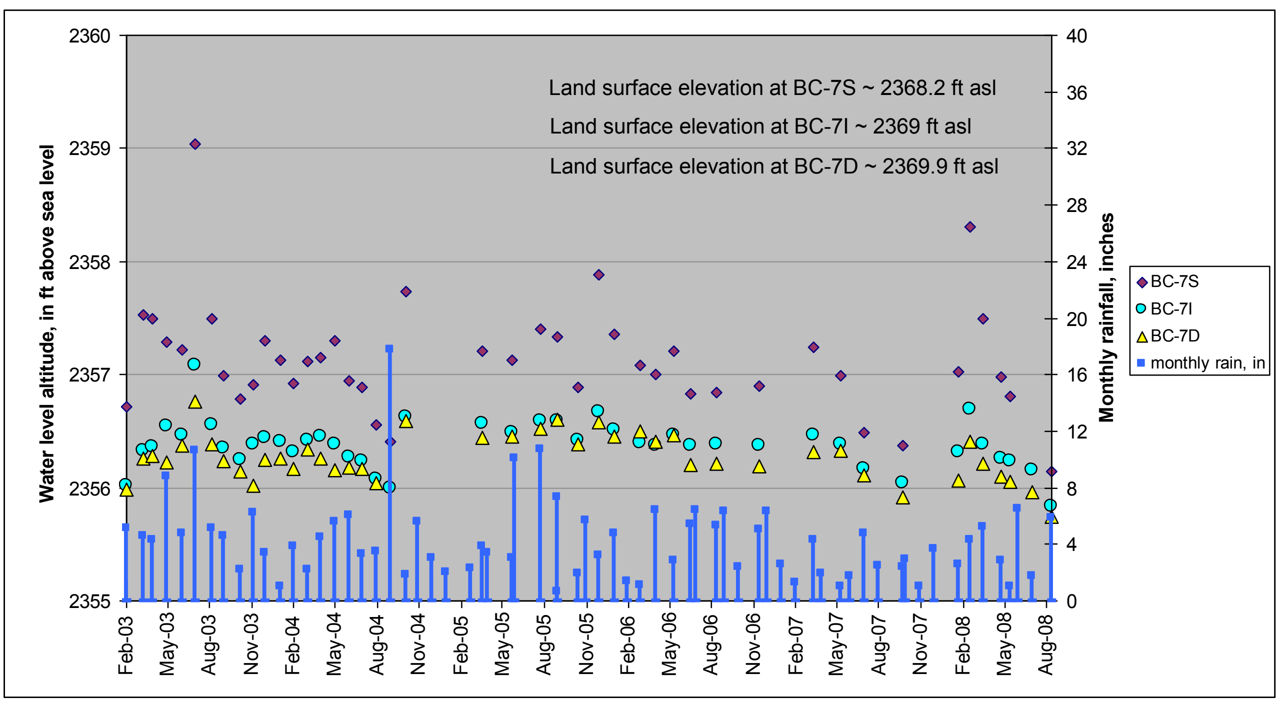


Figure 25D. Monthly water level measurements in cluster wells at site BC-7, a recharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

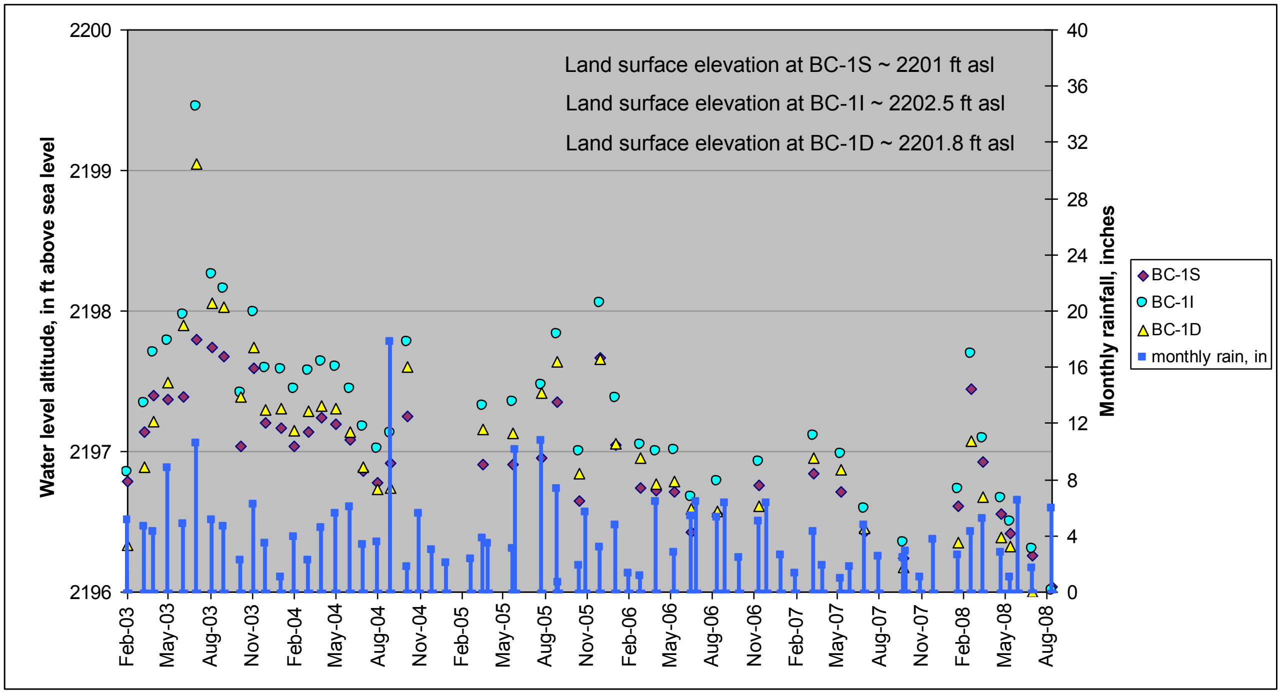


Figure 25E. Monthly water level measurements at cluster wells at site BC-1, a discharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

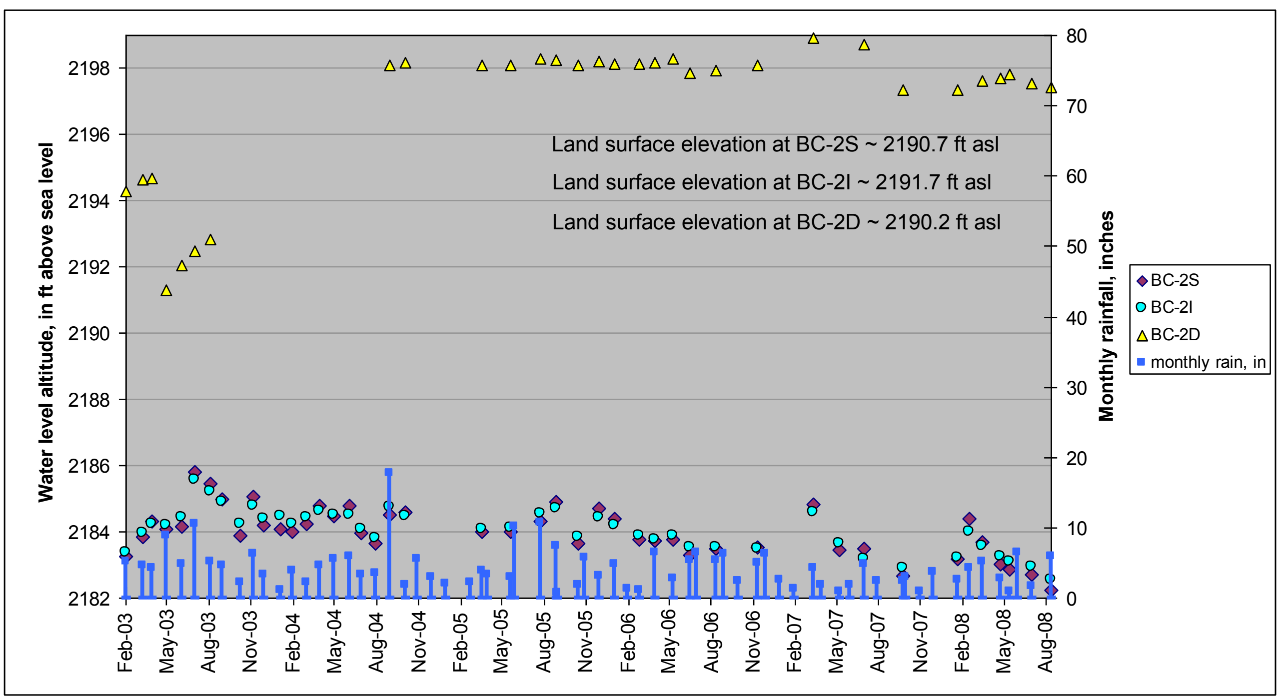


Figure 25F. Monthly water level measurements at cluster wells at site BC-2, a discharge area, in relation to monthly rainfall, Bent Creek Research Station, February 2003 to August 2008.

Table 8. Low and high water levels, average water levels, and total fluctuation during the period of record, and depth to water on August 14, 2008, in wells at Bent Creek Research Station, North Carolina.

Well	Low water table DTW, in ft bls	High water table DTW, in ft bls	Average water table DTW, in ft bls	Range (difference between high and low water table) ft	Depth to water on August 14, 2008 ft bls
BC-1S[a]	5.0	3.2	4.0	1.8	5.0
BC-1I[a]	6.5	3.1	5.2	3.4	6.5
BC-1D[a]	6.0	2.7	4.7	3.3	6.0
BC-2S[a]	8.4	4.9	6.7	3.6	8.4
BC-2I[a]	9.1	6.1	7.6	3.0	9.1
BC-2D[a]	[8.9][d]	[1.2][d]	[6.0][d]	7.8	[7.26][d]
BC-3S[a]	11.1	7.0	8.6	4.1	11.1
BC-3I[a]	10.5	6.9	8.3	3.6	10.5
BC-3D[a]	10.5	7.7	9.0	2.9	10.5
BC-4S[a]	10.4	6.8	8.7	3.6	10.4
BC-4I[a]	10.0	6.8	8.4	3.2	10.0
BC-4D[a]	13.2	10.9	11.9	2.3	13.2
BC-5S[a]	7.6	3.2	5.1	4.4	7.6
BC-5I[a]	9.9	6.0	7.7	3.9	9.9
BC-5D[a]	12.7	8.8	10.5	3.9	12.7
BC-6D[b]	33.9	31.0	32.1	2.9	33.5
BC-7S[a]	12.1	9.2	11.1	2.9	12.1
BC-7I[a]	13.2	12.0	12.7	1.2	13.2
BC-7D[a]	14.1	13.1	13.6	1.0	14.1
P1S[c]	10.6	8.2	8.6	2.4	10.6
P1I[c]	10.3	7.7	8.3	2.6	10.3
P2S[c]	8.6	5.6	6.2	3.0	8.6
P2I[c]	9.1	7.5	7.8	1.6	9.1
P3S[c]	8.6	6.0	6.5	2.7	8.6
P4S[c]	14.2	11.9	12.5	2.2	14.2
P4I[c]	14.6	12.7	13.1	1.9	14.6
P5S[c]	9.1	6.7	7.2	2.4	9.1
P5I[c]	8.2	7.3	7.5	0.9	
P6S[c]	8.7	6.5	6.9	2.2	8.7
P6I[c]	8.6	6.4	6.7	2.2	8.6
P7S[c]	10.0	7.4	7.9	2.5	10.0
P7I[c]	11.5	8.8	9.3	2.7	11.5
P8S[c]	5.1	2.7	3.1	2.4	5.1
P8I[c]	4.7	2.4	2.8	2.3	4.7
Average, all wells	10.5	7.8	8.8	2.8	10.5
Median, all wells	10.0	6.9	7.9	2.7	10.0
Minimum, all wells	4.7	2.4	2.8	0.9	4.7
Maximum, all wells	33.9	31.0	32.1	7.8	33.5

[a]Based on measurements made approximately monthly (n = 46 measurements) between February 2003 and November 2008;
[b]Based on measurements made approximately monthly (n = 20 measurements) between December 2005 and November 2008;
[c]Based on measurements made approximately monthly (n = 21 measurements) between February 2005 and August 2008;
[d]value shown is feet above land surface; DTW, depth to water; ft bls, feet below land surface

Table 9. Summarized water level fluctuations during the period the period of record for regolith wells and bedrock wells at Bent Creek Research Station, North Carolina.

Range (Maximum Minus Minimum for a Given Well) in Water Levels Over Period of Record[a], in feet

	regolith wells	open hole bedrock wells[b]
maximum	4.4 (BC-5S)	3.9 (BC-5D)
minimum	0.9 (P5I)	1.0 (BC-7D)
median	2.3	1.9

[a] Water levels as measured approximately monthly during period from February 2003 to November 2008; [b] Does not include BC-2D, an artesian, flowing well which had a range of 7.8 ft during the period of record.

Storm events produced a rapid, temporary increase in water levels in regolith and bedrock wells. At BC-7S, located in a midslope recharge area, storm-induced water level increases of about 1 foot were observed within 4 to 6 hours of numerous rainfall events throughout the period of hourly record (examples are shown in figs. 26). At BC-2S and -2I, located in a low-lying discharge area, storm-induced water level increases of about 1 to 3 ft were observed within 3 to 4 hours of numerous rainfall events throughout the period of hourly record (examples are shown in fig. 27). In general, the temporary storm-induced rise in both wells returned to within about 20 percent of the pre-storm levels within about 4 to 8 days. The amount of water level rise is a function of atmospheric pressure, rainfall amount, rainfall intensity, antecedent soil moisture, and geologic conditions. Water levels measured manually up to a day after storm events also showed similar rises in upper regolith, lower regolith, and bedrock wells at clusters P8[9], BC-4, and BC-1 (written communication, T. Campbell, January 20, 2011).

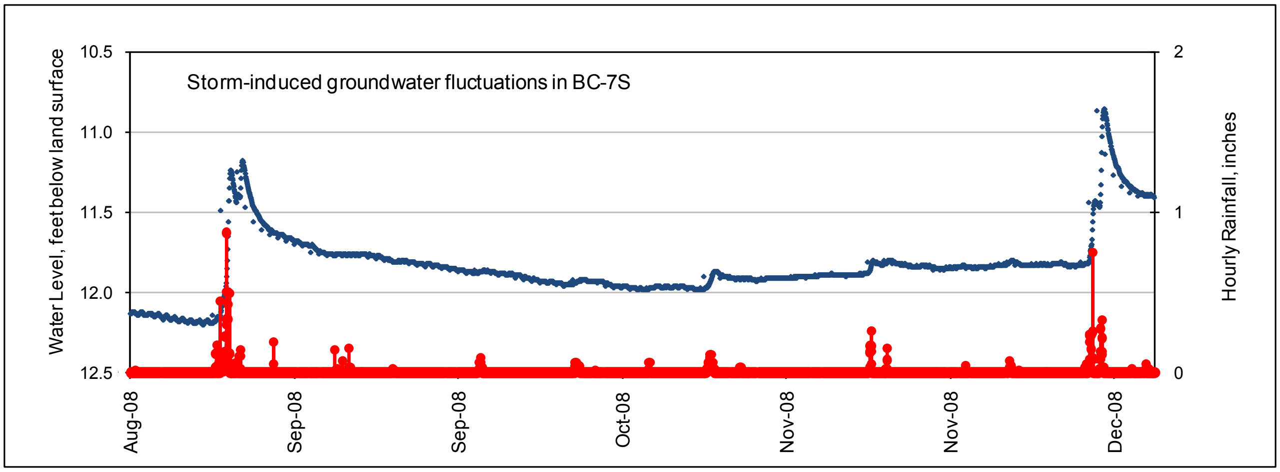
Vertical Head Gradients Between Upper Regolith, Lower Regolith, and Bedrock Flow Systems

Vertical head gradients observed at clustered wells were used to evaluate vertical movement of groundwater between different zones of the flow system. Vertical head gradients from the regolith system downward to the bedrock system were observed at sites BC-3, -4, -5, and -7 (areas of recharge) (fig. 4 and fig. 25A-D). At BC-2, a discharge area associated with the flowing, artesian bedrock well BC-2D, vertical head gradients were strongly upward from the bedrock system to the regolith system, with a potentiometric surface about eight feet above land surface (fig. 25F). The vertical head gradient between the upper and lower regolith wells BC-2S and -2I tended to be very slightly upward (differences were typically less than a tenth of a foot), except in response to storm events when the gradient could be upward or downward and up to 0.7 ft (fig. 27). These general trends are common in the Piedmont and Blue Ridge Provinces and follow the conceptual model described by LeGrand (2004), Harned and Daniel (1992), and Heath (1983, 1984).

At BC-1, a flat, low-lying highly permeable discharge area adjacent to Bent Creek (fig. 4), a slight upward vertical head gradient was observed between upper and lower regolith wells BC-1S and -1I (typically about 0.3 ft, fig. 25E). Head gradients were slightly downward (typically about 0.2 ft) from the lower regolith well BC-1I to the bedrock well BC-1D, illustrating the fact that the potentiometric head in a bedrock well is a composite of the hydraulic heads of all fractures tapped by the well and, as such, may not represent conditions throughout the local discharge area. This suggests that care should be taken when evaluating recharge versus discharge conditions solely on the basis of vertical head

[9] A bedrock well not installed at P8.

gradients in a single cluster of wells. A more complete discussion of vertical flow at this site is presented in the section titled ‘Seasonal and Storm-Induced Groundwater Temperature Fluctuations’.



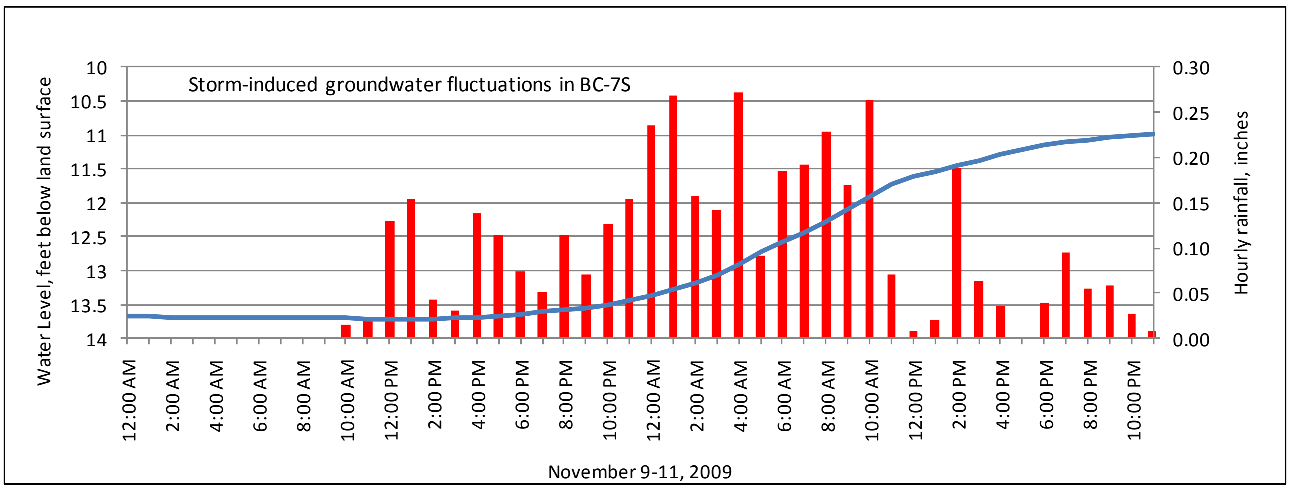
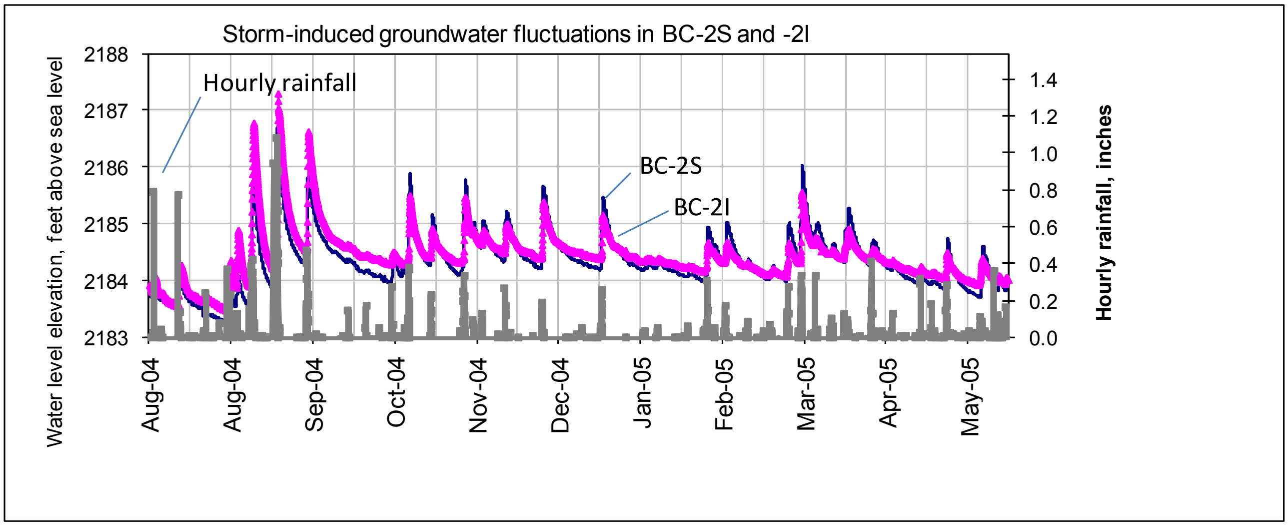


Fig. 26. Example of storm-induced water level fluctuations in upper regolith well BC-7S (recharge area), Bent Creek Research Station, North Carolina.



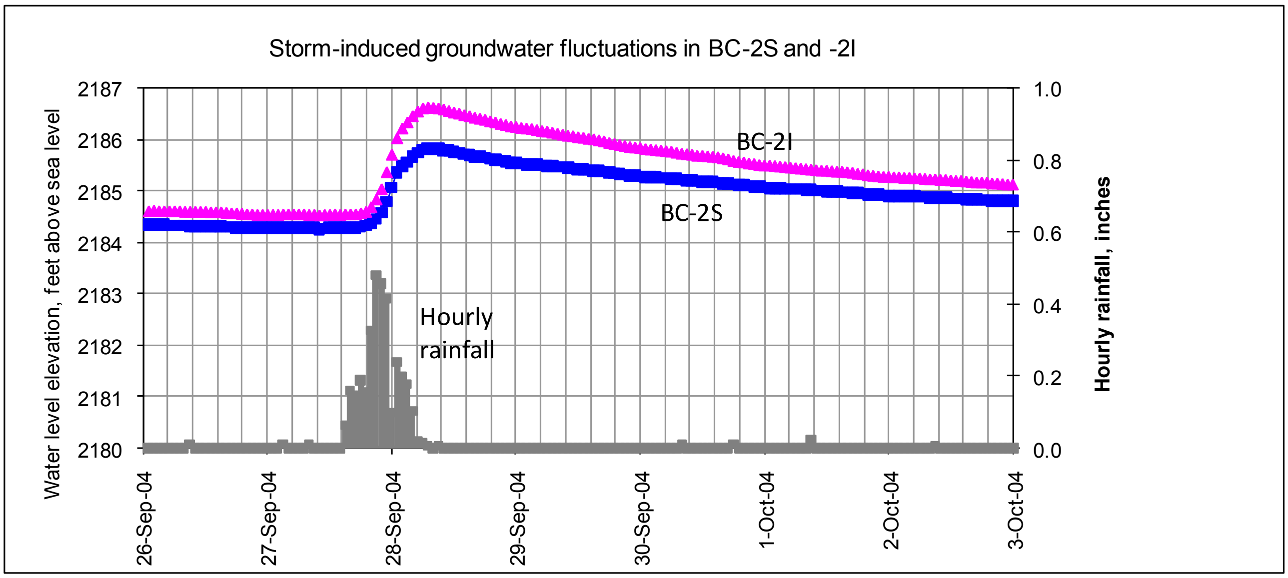


Fig. 27. Example of storm-induced water level fluctuations in upper and lower regolith wells BC-2S and -2I (discharge area), Bent Creek Research Station, North Carolina.

Seasonal and Storm-Induced Groundwater Temperature Fluctuations

Hourly water temperatures were recorded during various periods in several well clusters to observe seasonal and storm-induced response and inferred recharge, groundwater-surface water interactions, and vertical groundwater movement. Hourly water temperatures also were recorded in stream water and streambank sediment pore water of Boyd Branch near P8 (fig. 4). Storm response was observed using pressure transducer data loggers (recording both water levels and temperatures) for several months at two representative well clusters (BC-7 in a recharge setting and BC-2 in a discharge setting).

While water *levels* in the three flow zones fluctuated seasonally, water *temperatures* fluctuated seasonally only in upper regolith wells and in some lower regolith wells. Water *levels* in the three flow zones fluctuated in response to storms, but water *temperatures* responded to storms only in upper regolith wells. Water temperatures in all measured bedrock wells were stable throughout the measurement period.

Water temperatures in all upper regolith wells, regardless of hydrologic setting (recharge or discharge), fluctuated seasonally by at least 3° (and up to 14° F) in response to seasonal air temperatures. However, water temperatures in lower regolith wells (data available only in discharge areas) fluctuated seasonally by only 1 to 2° F in response to seasonal air temperatures (table 10).

At BC-4, a midslope recharge area (fig. 4) with downward vertical head gradients, water temperatures recorded from July 2008 to January 2009 in upper regolith well BC-4S lagged seasonal air temperatures by about 4 months and fluctuated 3° F (ranging from 54° to 57° F)(fig. 28; table 10). Water temperatures in bedrock well BC-4D remained stable at 55° F throughout the measurement period, and temperature data were not collected in lower regolith well BC-4I.

Storm-induced temperature fluctuations at BC-4 suggest a close hydraulic connection between shallow groundwater and rainfall recharge. For example, rainfall on August 26 (1.5 inches in one hour) and on August 27, 2008 (4 inches in one hour), a time during which air and rainfall temperatures are seasonally warmer than groundwater temperatures, produced a temporary temperature increase in upper regolith well BC-4S (fig. 29) and lagged the rainfall event by about 10 hours. This was typical of the temperature lag time associated with other rainfall events at this location.

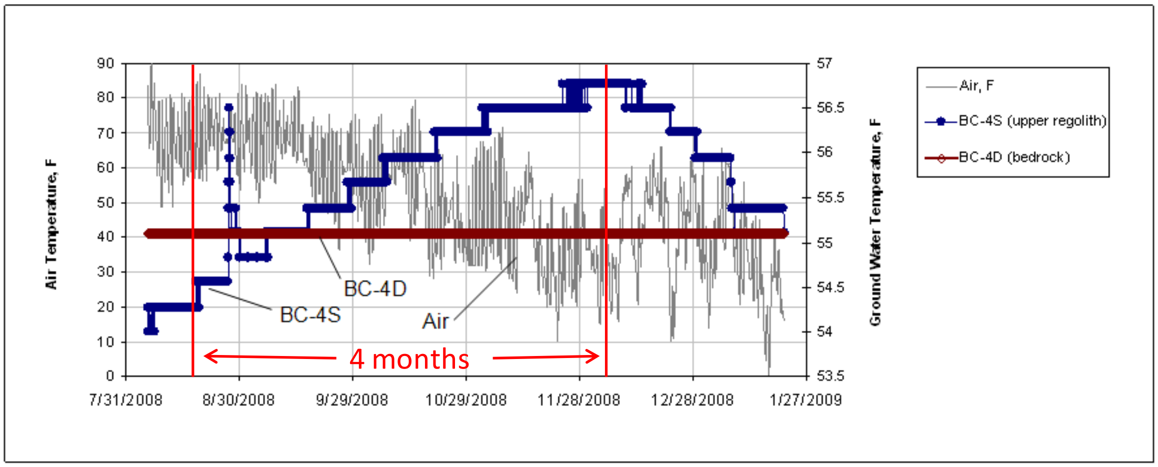


Figure 28. Seasonal temperature fluctuations in upper regolith well BC-4S and bedrock well BC-4D (recharge area), in relation to air temperatures, July 2008 to January 2009, Bent Creek Research Station, North Carolina.

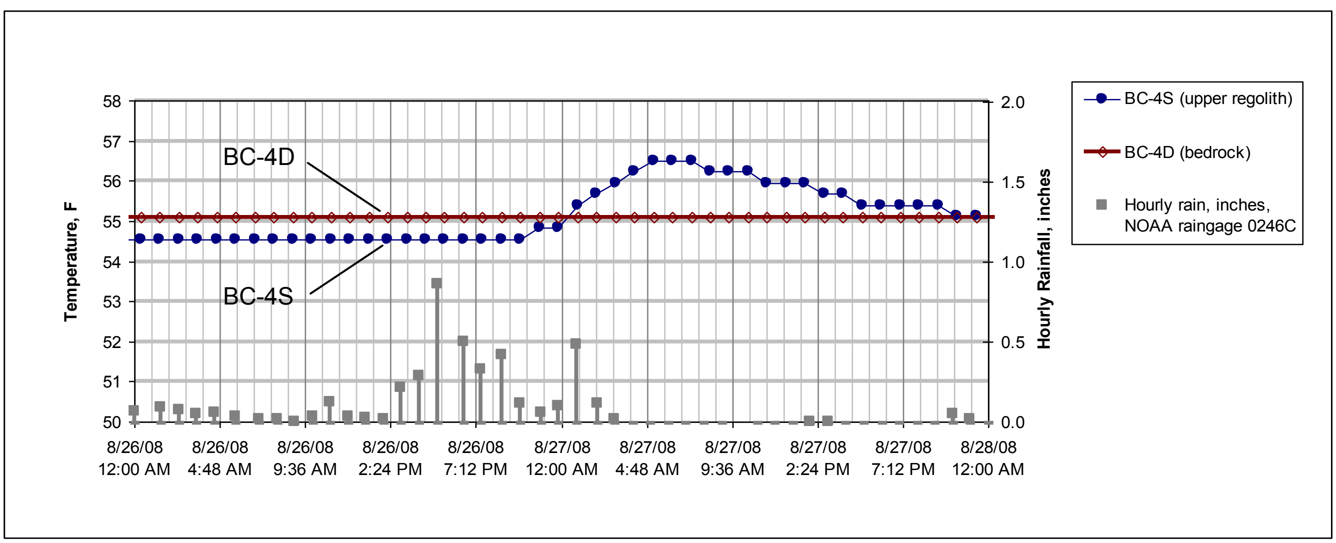


Figure 29. Storm-induced temperature fluctuations in upper regolith well BC-4S and bedrock well BC-4D (recharge area), in response to summer storm event, August 26 to 28, 2008, Bent Creek Research Station, North Carolina.

Table 10. Temperature fluctuations in different portions of flow system in response to seasonal climate and short-term rainfall events, Bent Creek Research Station, North Carolina.

	Portion of flow system	Daily Temperature Fluctuation	Seasonal Temperature Fluctuation	Rainfall-Induced Temperature Fluctuation	Vertical potentiometric head gradient
Recharge areas					
Site BC-4	Upper regolith, BC-4S	none	54 to 57° F (3°) with 4 month lag	2° with 10 hour lag	Downward gradient to lower regolith
	Lower regolith, BC-4I	not measured	not measured	not measured	Downward gradient to bedrock
	Bedrock, BC-4D	none	no seasonal fluctuation (stable 55° F)	no rainfall-induced fluctuation	----
Site BC-7	Upper regolith, BC-7S	none	55 to 58° F (3°) with 4 month lag	no rainfall-induced fluctuation	Downward gradient to lower regolith
	Lower regolith, BC-7I	not measured	not measured	not measured	Downward gradient to bedrock
	Bedrock, BC-7D	not measured	not measured	not measured	----
Discharge areas					
Site P8[a]	Upper regolith, P8S	none	54 to 57° F (3°) with 3 month lag	no rainfall-induced fluctuation	----
	Lower regolith, P8I	none	54 to 56° F (2°) with 4 month lag	no rainfall-induced fluctuation	Slight Upward gradient to upper regolith
	Boyd Branch stream water	4 to 9°	32 to 72° F (40°) with 2 hour lag		
	Bank sediment pore water	1 to 2°	35 to 69° F (34°) with 7 hour lag		
Site BC-1	Upper regolith, BC-1S	none	49 to 63° F (14°) with 1 month lag	1 to 2° with 1 to 2 day lag	
	Lower regolith, BC-1I	none	54 to 55° F (1°) with 5 month lag	no rainfall-induced fluctuation	Upward gradient to upper regolith, and slight downward gradient to bedrock
	Bedrock, BC-1D	none	no seasonal fluctuation (stable 55° F)	no rainfall-induced fluctuation	
Site BC-2	Upper regolith, BC-2S	none	52 to 58° F (6°) with 3 month lag	1 to 2° with 5 to 10 hour lag	----
	Lower regolith, BC-2I	none	53 to 54° F (1°) with 7 month lag	no rainfall-induced fluctuation	Neutral / slight upward gradient to upper regolith
	Bedrock, BC-2D	none	no seasonal fluctuation (stable 55° F)	no rainfall-induced fluctuation	Strong upward gradient to regolith
Other					
Air	not applicable	10 to 35°	3 to 89° F (86°)	not applicable	not applicable

[a] Site P8 is an area of very slight discharge.

At BC-7, another midslope recharge area (fig. 4), water temperatures recorded from February 2009 to June 2009 in upper regolith well BC-7S lagged seasonal air temperatures by about 4 months and fluctuated 3° F (ranging from 55 to at least 58° F)(fig. 30).

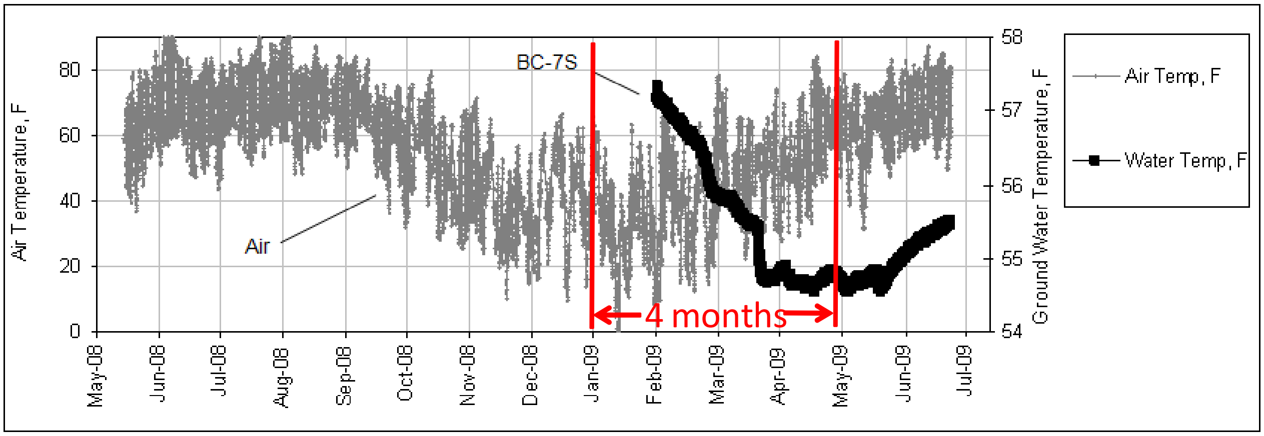


Figure 30. Seasonal temperature fluctuations in upper regolith well BC-7S (recharge area), in relation to air temperatures, May 2008 to June 2009, Bent Creek Research Station, North Carolina.

At P8, located midslope and about 30 ft from Boyd Branch (fig. 4), water temperatures recorded from August 2008 to February 2009 in upper regolith piezometer P8S and lower regolith piezometer P8I lagged seasonal air temperatures by about 3 and 4 months, respectively, and fluctuated about 3° (ranging from 54° to 57° F) and 2° (ranging from 54° to 56° F), respectively (fig. 31C). P8 was defined as an area of transition from recharge to discharge, based on very slight to near neutral vertical head gradients in clustered regolith piezometers measured approximately monthly. About 15 feet away, water temperatures in Boyd Branch fluctuated daily (typically about 4° to 9° F) and seasonally (ranging from 32° to 72° F), and lagged air temperatures (ranging from 3° to 89° F) by about 2 hours (figs. 31A and B). Streambank sediment pore water temperatures fluctuated daily (typically about 1° to 2° F) and seasonally (ranging from 35° to 69° F), and lagged stream temperatures by about 5 hours (figs. 31A and B). As expected, in summer months temperatures in stream water and in streambed sediment pores were warmer than shallow groundwater (fig. 31B). The reverse was true in winter months. Daily temperature fluctuations were not observed in regolith piezometers P8S and P8I (fig. 31A).

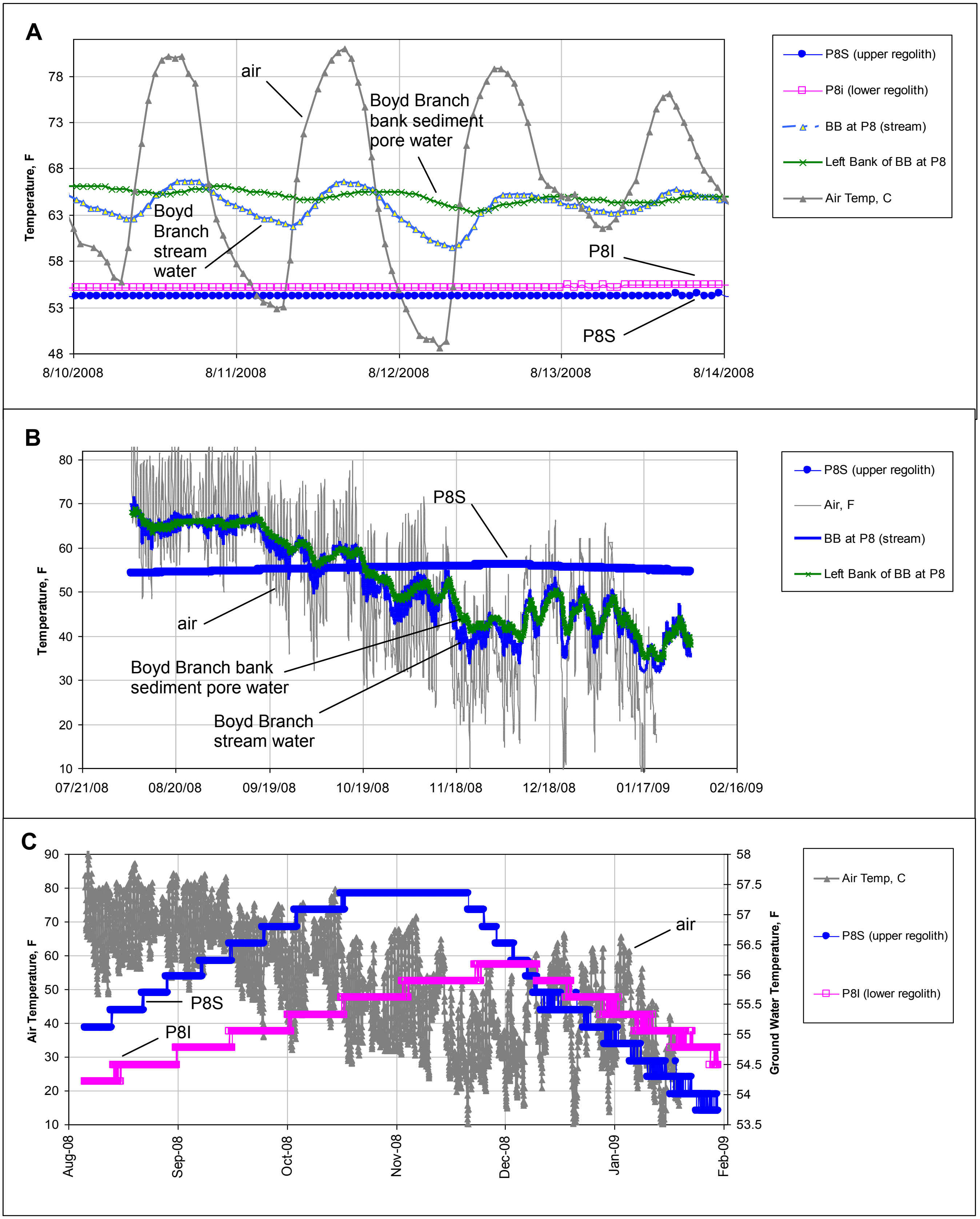


Figure 31. (A) Diurnal temperature fluctuations in upper regolith piezometer P8S, lower regolith piezometer P8I, Boyd Branch stream water, and streambank sediment pore water, August 10 to 14, 2008, and (B) and (C) seasonal temperature fluctuations in P8S, P8I, Boyd Branch stream water, and streambank sediment pore water, August 2008 to February 2009, in relation to air temperatures, Bent Creek Research Station, North Carolina.

At BC-1, a flat, low-lying highly permeable discharge area adjacent to Bent Creek (fig. 4), groundwater in the upper regolith system is inferred to be a mixture of vertically up-welled water from the lower regolith system and water from the Bent Creek hyporheic zone. This observation is based on a slight upward vertical head gradient that was observed between upper and lower regolith wells BC-1S and -1I (typically about 0.3 ft, fig. 25E) and hourly water temperature measurements of the different flow zones (figs. 32 A and B).

Rainfall on August 26 (1.5 inches in one hour) and on August 27, 2008 (4 inches in one hour), a time during which air and rainfall temperatures are warmer than groundwater temperatures, produced a temporary, slight *decrease* in water temperature in upper regolith well BC-1S (fig. 32). This suggests that cooler water from the lower regolith (and possibly bedrock system) temporarily up-welled during the summer precipitation event, an occurrence documented at a groundwater research station in the Piedmont (Lake Wheeler Road Research Station, Chapman and others, 2005). Conversely, rainfall on December 10 (2.1 inches in one hour) and December 11, 2008 (1.5 inches in one hour), a time during which air and rainfall temperatures were mostly cooler than groundwater temperatures, produced a temporary, slight *increase* in temperature in groundwater in BC-1S (fig. 32B). This suggests that warmer water from the lower regolith (and possibly bedrock system) temporarily up-welled during the winter precipitation event. These observations are consistent with conditions in a discharge area with upward head gradients such as those at this site. In general, the storm-induced temperature fluctuations in BC-1S resulting from up-welled water lagged a typical rainfall event by about 1 to 2 days. The water temperature in lower regolith well BC-1I and bedrock well BC-1D remained stable (about 55^{o} F) during all storm events (figs. 32A and B).

Seasonal groundwater temperature fluctuations recorded from August 2008 to February 2009 in upper regolith well BC-1S lagged seasonal air temperatures by about 1 month and fluctuated about 14^{o} F (ranging from 49^{o} to 63^{o} F)(fig. 33). This is a more rapid climate response than at midslope recharge areas BC-4 and BC-7 (where shallow water temperatures fluctuated only 3^{o} F and lagged air temperature by about 4 months) and appears to be due to a shallower water table, a more permeable aquifer matrix (alluvium, colluviums, and transition zone material), and a closer proximity to and greater mixing with stream water at BC-1 than at the two midslope locations[10]. Temperatures recorded in the lower regolith well BC-1I fluctuated only slightly (ranging from 54^{o} to 55^{o} F), and lagged seasonal air temperatures by about 5 months (fig. 33). Temperatures in bedrock well BC-1D (about 55^{o} F) remained stable (fig. 33) throughout the period of measurement.

[10] BC-1S is within about 60 ft of Bent Creek (fig. 34). Well BC-1S is screened across highly permeable alluvium in a discharge area (k = 30 ft/day), whereas BC-4S and BC-7S are screened across less permeable saprolite in recharge areas (k = 2 and 0.2 ft/day, respectively). Because of its location in an alluvial fan at the base of the watershed and adjacent to Bent Creek, BC-1S is expected to be in close hydraulic communication with surface water in Bent Creek.

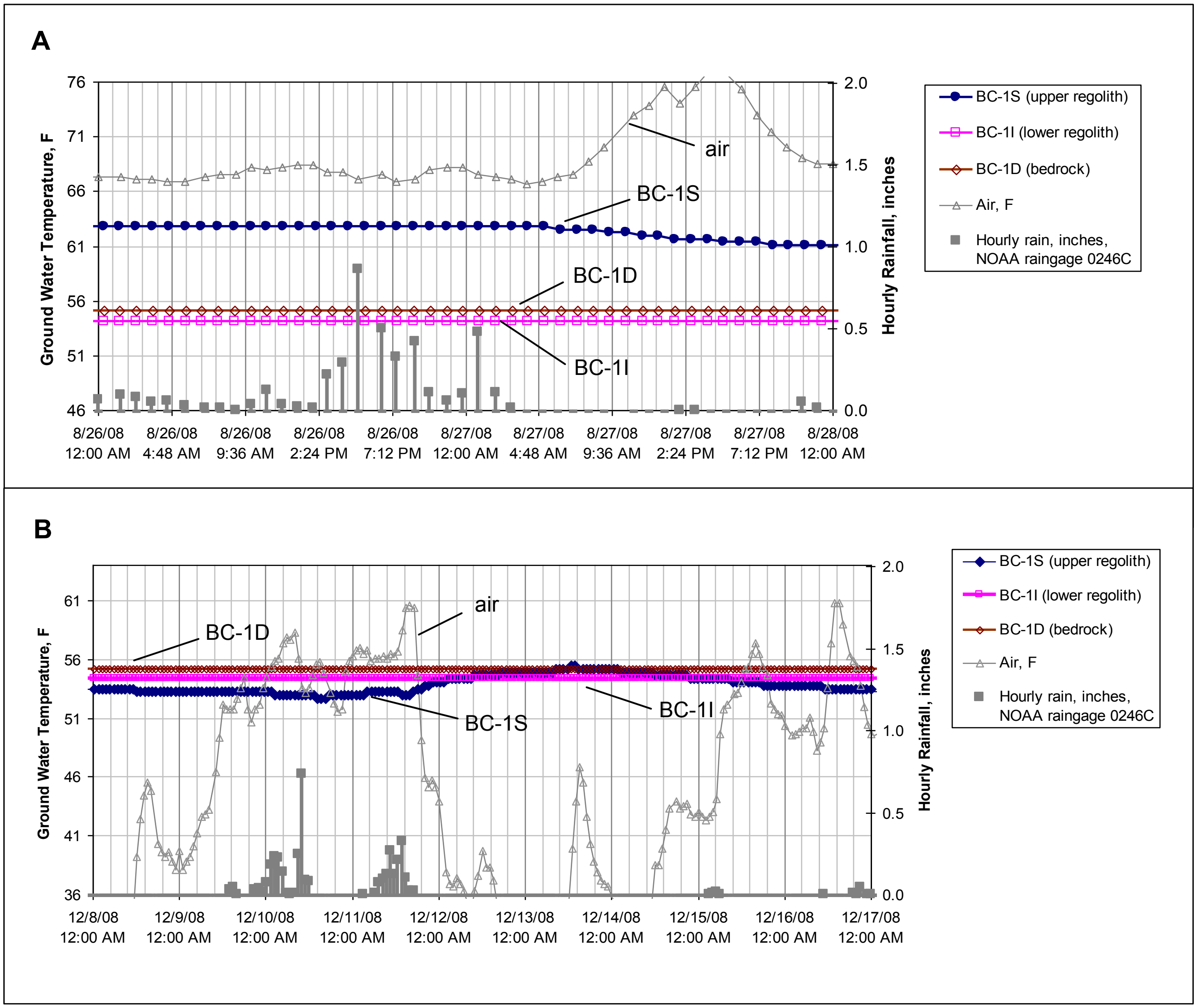


Figure 32. Storm-induced temperature fluctuations in upper and lower regolith wells BC-1S and -1I and bedrock well BC-1D (discharge area), in response to (A) hourly rainfall and air temperatures during a summer storm event, August 26, 2008, and (B) hourly rainfall and air temperatures during an early winter storm event, December 8 to 17, 2008, Bent Creek Research Station, North Carolina.

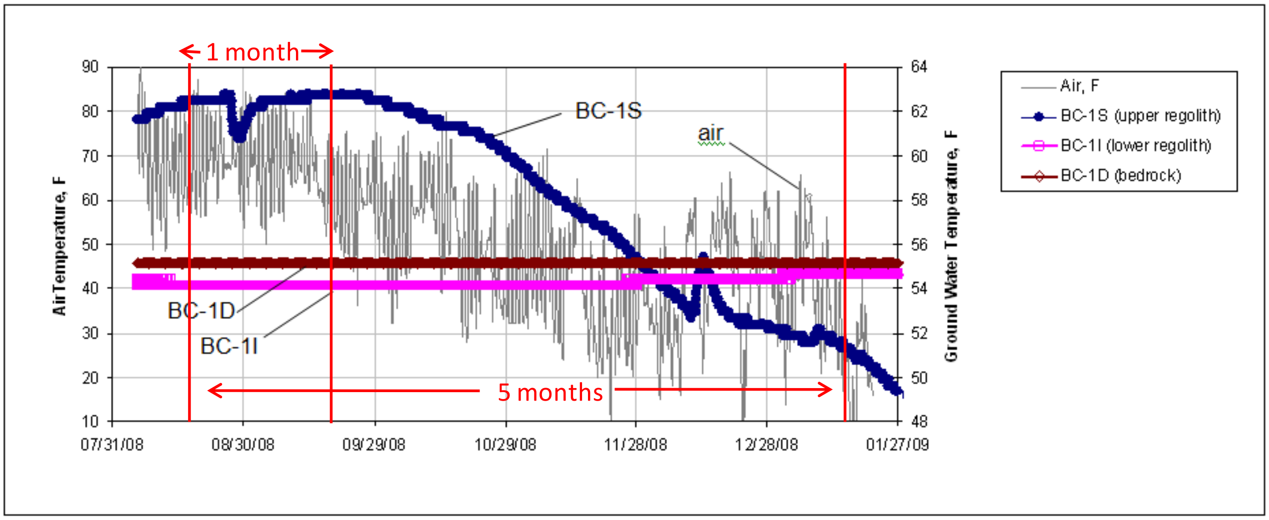


Figure 33. Seasonal temperature fluctuations in upper regolith well BC-1S (discharge area), in relation to air temperatures, July 2008 to January 2009, Bent Creek Research Station, North Carolina.

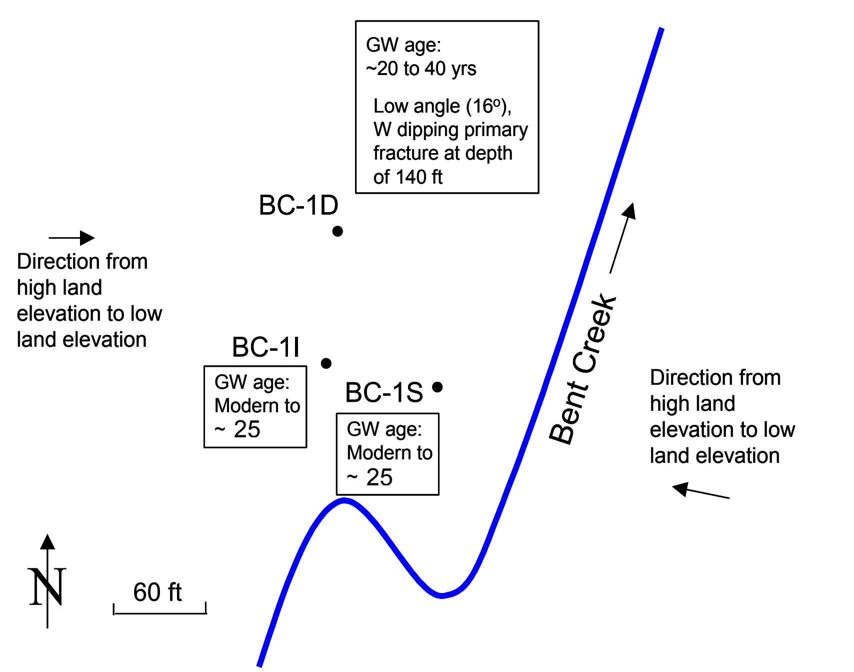


Figure 34. Monitor wells and ground water ages at site BC-1 located in low-lying discharge area, Bent Creek Research Station, North Carolina.

At BC-2, despite the upward vertical head gradients characteristic of a low-lying discharge area, water temperature data suggested a close hydraulic connection between groundwater in the upper regolith system and recharge events. Temperature in upper regolith well BC-2S fluctuated about 1 to 2^{o} F in response to storm events (figs. 35A and 36A). As such, recharge was inferred to occur to the shallowest part of the groundwater system, even though the net flux of groundwater at the site is upward from bedrock to regolith. Temperatures in lower regolith well BC-2I and bedrock well BC-2D remained stable at about 54^{o} and 55.5^{o} F respectively (figs. 35B and 36B). For example, a storm event on September 27, 2004 (3.1 inches in 12 hours), a time during which air and rainfall temperatures are warmer than groundwater temperatures, produced a temporary increase in temperature of about 0.8^{o} F in shallow groundwater in BC-2S (fig. 35A). A storm event on January 13, 2005 (1.2 inches in 12 hours, a time during which air and rainfall temperatures are cooler than groundwater temperatures, produced a temporary decrease in temperature of about 1.5^{o} F in shallow groundwater in BC-2S (fig. 36A). These upper regolith temperature trends were counter to those in BC-1S in the more permeable discharge area adjacent to Bent Creek, which was associated with upwelling and mixing with stream water. In general, the rainfall-induced temperature fluctuations in BC-2S lagged the start of a typical rainfall event by about 5 to 10 hours.

Temperatures recorded in upper regolith well BC-2S lagged seasonal air temperatures by about 3 months and fluctuated about 6^{o} F (ranging from 52^{o} to 58^{o} F)(fig. 37). This fluctuation is far less than the 14^{o} observed at BC-1S in the discharge area adjacent to Bent Creek and appears to be due to the fact that BC-2S is less affected by stream interactions and is underlain by less a less permeable aquifer matrix than BC-1S[11]. Water temperatures in lower regolith well BC-2I fluctuated only slightly (ranging from 53^{o} to 54^{o} F) and lagged seasonal air temperatures by about 7 months (fig. 37). Temperature in bedrock well BC-2D remained stable at 55^{o} F.

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[11] BC-2S is located 150 feet from the 2nd order Boyd Branch and is screened across only moderately permeable saprolite material (k = 3 ft/day), while BC-1S is only 60 feet from the 3rd order Bent Creek and is screened across mostly alluvium, colluviums, and transition zone material (k = 30 ft/day).

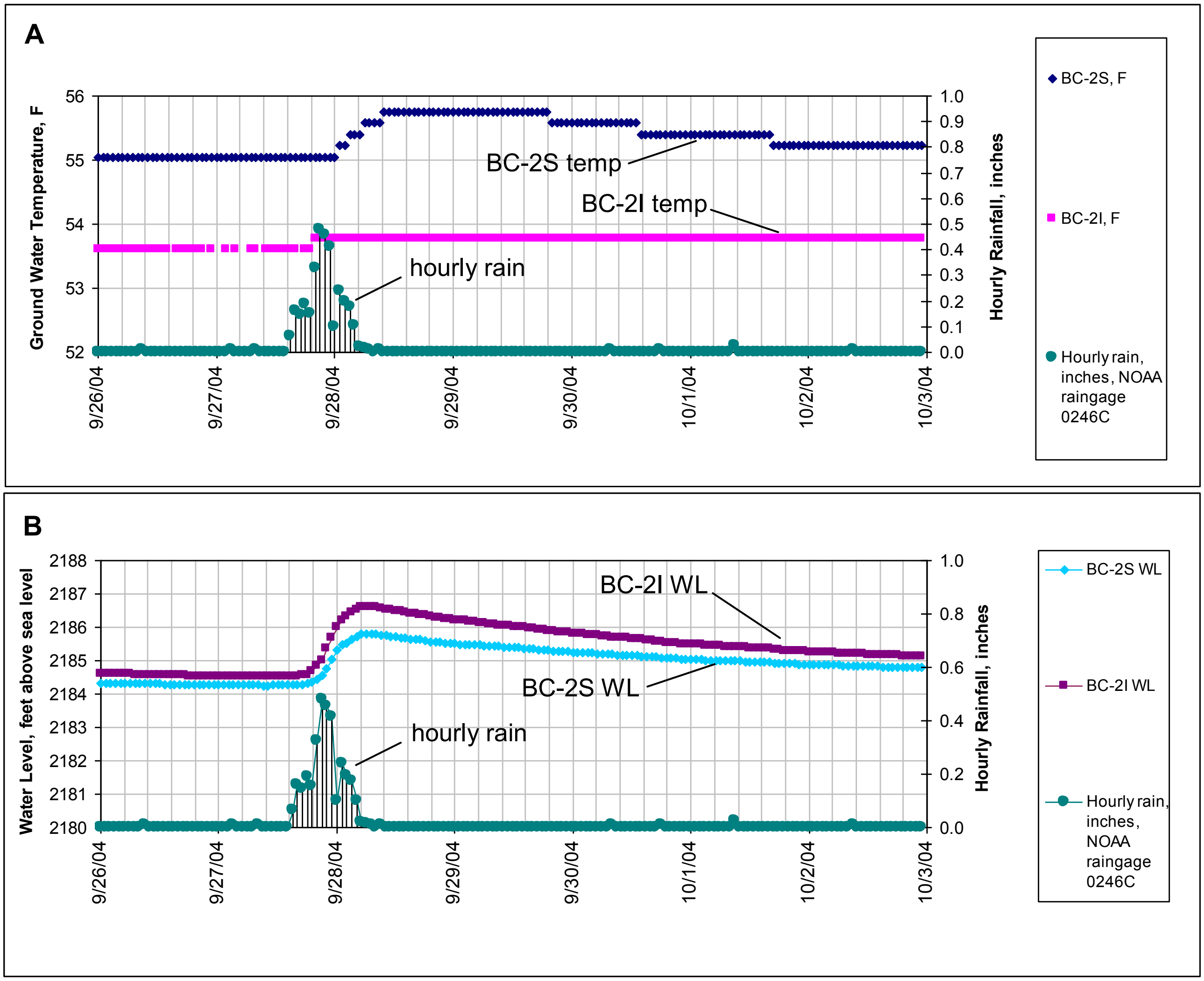

Figure 35. (A) Storm-induced temperature fluctuations in upper and lower regolith wells BC-2S and -2I (discharge area), and (B) storm-induced water level fluctuations at BC-2S and BC-2I, in response to late summer storm event, September 26 to October 3, 2004, Bent Creek Research Station, North Carolina.

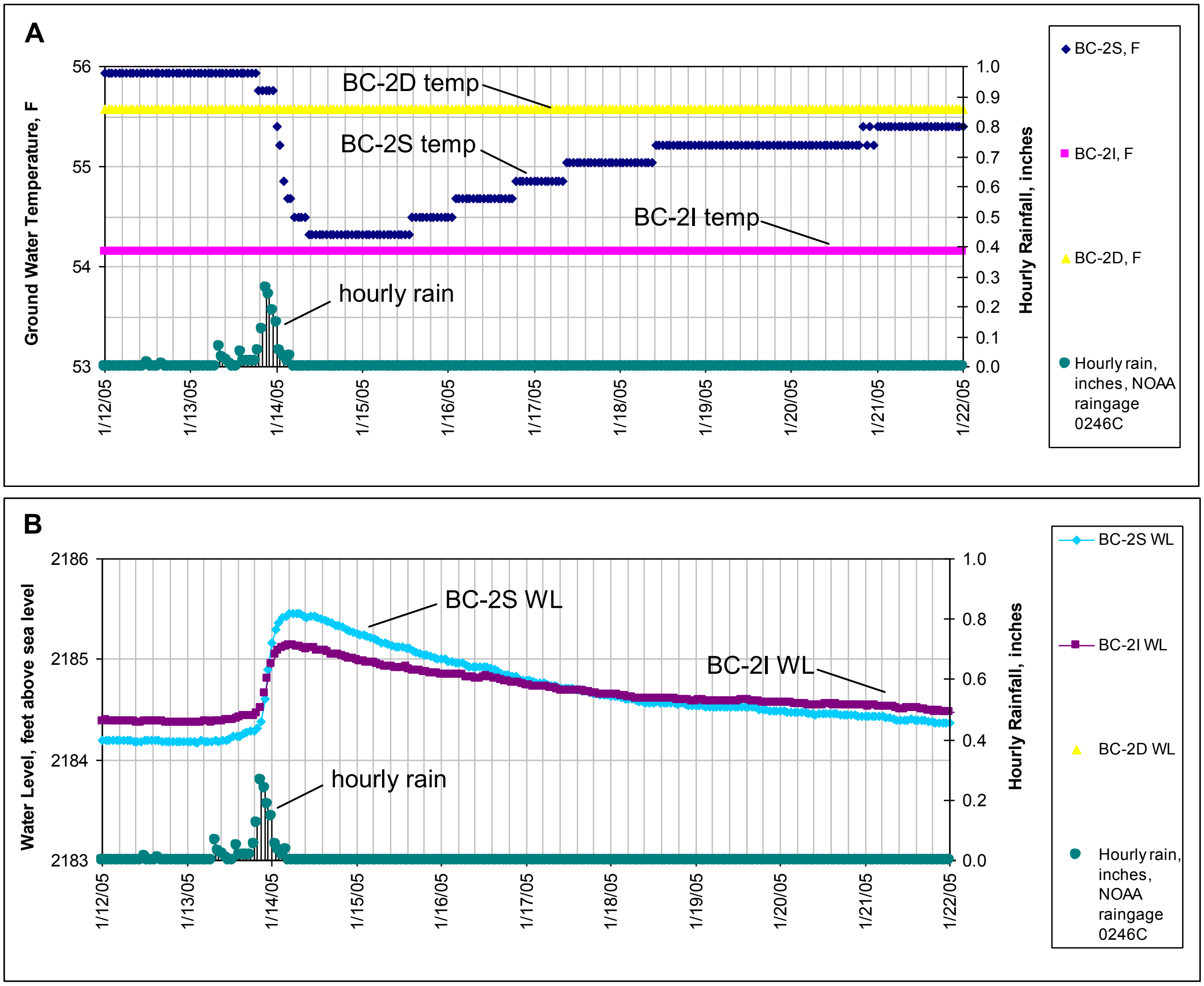

Figure 36. Storm-induced temperature fluctuations in upper and lower regolith wells BC-2S and -2I (discharge area), and (B) storm-induced water level fluctuations at BC-2S and BC-2I, in response to winter storm event, January 12 to January 22, 2005, Bent Creek Research Station, North Carolina.

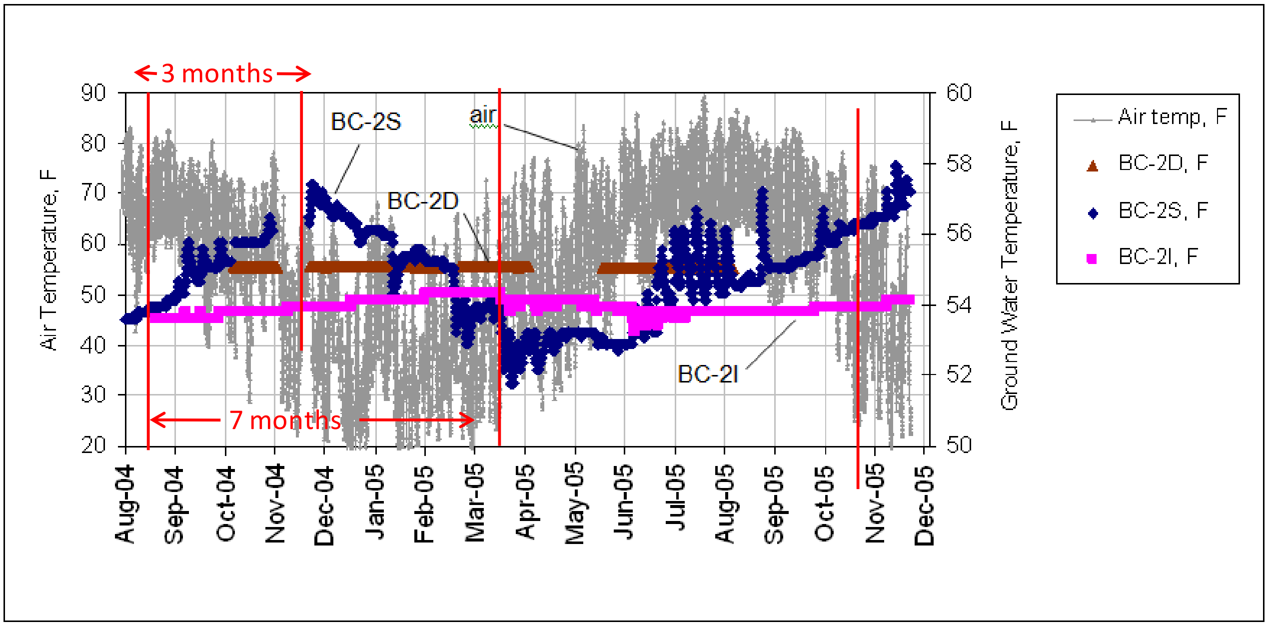

Figure 37. Seasonal temperature fluctuations in upper and lower regolith wells BC-2S and -2I and bedrock well BC-2D (discharge area), in relation to air temperatures, August 2004 to December 2005, Bent Creek Research Station, North Carolina.

Aquifer Response to 72-Hour Pumping in Regolith

A 72-hour aquifer pumping test was conducted in lower regolith well BC-4I to evaluate the (1) the degree of interconnectivity between the upper regolith (saprolite), lower regolith (transition zone), and bedrock flow systems; (2) the degree of heterogeneity and preferential flow paths within the system; and (3) the lateral extent of influence due to pumping. Because of the complexity of the three-part, dual porosity, non-homogeneous, fractured, and anisotropic flow system, a presentation of analytical modeling and quantitative determinations of aquifer properties was beyond the scope of this report.

The aquifer system was conceptualized as being under unconfined hydraulic conditions as evidenced by the very small vertical head gradients in clustered wells (or, where a vertical gradient exists, the head in the shallow regolith well is greater than the head in the deeper transition zone well) and the absence of a noted confining layer within the regolith itself. The bottom boundary of the regolith flow system was fractured bedrock. This boundary was considered to be slightly leaky, as evidenced by the connectivity between the pumping well BC-4I and the adjacent deep bedrock well BC-4D (total water level drawdown in BC-4D during pumping was about 1.2 ft), though the quantity of water available as storage in the fractures themselves was assumed to be minor when compared to the quantity of water in storage in the regolith. Rainfall recharge to the unconfined aquifer system flows through the upper and lower regolith and discharges to parts of Boyd Branch or Bent Creek. The remainder infiltrates to underlying bedrock fractures and moves downgradient in response to hydraulic head gradients. The upper regolith consists of a variably thick unit of loamy sand, silt, and clay saprolite that is porous, heterogeneous, and anisotropic and extends to a depth of 20 to 30 ft bls. The lower regolith is 10 to 20 ft thick and consists of a much more transmissive unit of partially weathered and unweathered parent rock that also is relatively porous, heterogeneous, and variably thick. Both the upper and lower regolith are expected to be vertically stratified (due to differential weathering of parent rock) and anisotropic (due to relict foliations, fractures, and veins). Neither the pumping well nor the observation wells fully penetrated the entire saturated regolith thickness so vertically stratified flow was expected in the early portion of the test. Fractured bedrock occurs at a depth of about 40 to 45 ft bls.

Pumping occurred in well BC-4I, which was 41 feet in depth, 4 inches in diameter, and screened from 26 to 41 feet bls. The top 3 feet of screen (26 to 29 feet bls) was open to saprolite, and the remaining 12 feet of screen (from 29 to 41 ft bls) was open to transition zone material. The pump was set at a depth of 41 ft bls and was operated at a relatively constant flow rate of 20 gpm for 72 hours from October 11 to 14, 2004. Water levels were measured throughout the test in ten well/piezometer clusters[12] (19 observation wells in all) and at two staff gages in Boyd Branch (fig. 38A). Clustered wells screened in the upper regolith and lower regolith (BC-4S and I, P1S and I, P5S and I, P6S and I, P7S and I, P8S and I, P2S and I, and BC-5S and I, fig. 38A) were used to evaluate the degree of interconnectivity between different parts of the regolith flow system. Bedrock well BC-4D was used to observe connectivity between the regolith and fractured bedrock portions of the groundwater system. Wells positioned in a radial pattern or along perpendicular transects were used to observe anisotropy and the shape and extent of the zone of pumping influence. Assuming that the weathered parent rock retains distinct foliations and therefore preferred pathways, then both the saprolite and transition zone could be anisotropic, both horizontally and vertically.

Three transects were used to analyze drawdown: A-A', oriented in the approximate direction of presumed foliation strike: BC-4I, P6S and I, P8S and I, and Boyd Branch; B-B': BC-4I, BC-4S, P1S and I, and P7S and I; and C-C': BC-4I, P5S and I, P2S and I, and P3S. Geologic cross sections of the regolith were constructed for each transect using information obtained during coring and drilling (figs. 38A-D). Wells positioned very close to the pumping well (BC-4S, P1S and I, P6S and I, and P5S and I) were used to observe delay in the time-drawdown curve and to analyze aquifer characteristics in the vicinity of the pumping well. Distant wells (P8S and I, P7S and I, BC-5S and I, P2S and I, P3S, and P4S and I) were used to observe the distance that the cone of depression expanded during the test. Well locations and screen intervals are shown in table 11.

Determinations of depth to saprolite, transition zone, and bedrock were based on observed drill cuttings, auger penetration rates, and interpretations of rock core at BC-4. Interpolations were made between drilled locations. Some subjectivity arose when determining depths because the degree of weathering often varied over relatively short distances.

Aquifer characteristics in the test area were as follows[13]:

- The regolith was not of uniform thickness in the test area (figs. 38a to 38d). The saturated thickness of the regolith gradually thickened in the predominant groundwater flow direction from NW to SE, from about 8 feet at P7 to about 35 feet at BC-4I to about 55 feet at P2 (figs. 38A to 38D).
- Potential horizontal hydraulic boundaries in the test area were: (1) Boyd Branch, located about 240 feet northeast of pumping well BC-4I (figs. 38A and 38B), (2) a suspected schist-metagraywacke contact that is less than 400 feet west-northwest of BC-4I (figs. 38A and 38C), and (3) the thinned regolith flow system that nearly pinches out upslope in the vicinity of P7S (less than 250 feet west-northwest of BC-4I) (fig. 38C).
- A contact between mica schist and metagraywacke is projected to occur somewhere between the pumping well and P7 located 370 feet to the northwest, as mapped by Merschat and Carter (2002, appendix 1A) and drill cuttings.
- The location of the pumping test is near the base of a secondary synform fold as mapped by Merschat and Carter (2002, appendix 1A).

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[12] Observation wells in the upper and lower regolith included 2-inch diameter piezometers with 5-ft screen lengths and 4-inch diameter wells with 15-ft screen lengths. Observation wells in the bedrock were open hole with diameters of 6.25 inches.

[13] Conditions that deviated from uniform and homogeneous may result in a variety of effects that must be considered during analysis. For example, distinct changes in rock type could, in some localized areas, result in the upper regolith (saprolite) being only sluggishly connected to the lower regolith (transition zone). Partially penetrating well effects can produce time drawdown data that resemble that produced by a recharge boundary, an aquifer of variable thickness, or an aquifer experiencing downward leakage.

- Four outcrops within 1000 feet show vertical or near vertical foliation with a NE strike (average azimuth of about 36 degrees). Farther up slope, moderately dipping foliation also strikes NE (average azimuth of about 55 degrees). The foliation strike to the northeast appears to be a preferred pathway for groundwater flow in the regolith (which, though weathered, retains the fabric of its parent bedrock) and contributes to anisotropic conditions in the aquifer test area.
- Vertical gradients were slightly downward, minimal, or absent at clustered wells in the aquifer test area, suggestive of unconfined aquifer conditions. An exception to this was a very slight upward vertical gradient from the lower regolith well to the upper regolith well in the vicinity of P7.

Total drawdown in pumping well BC-4I was 5.2 feet, and total drawdown in the nearest saprolite, transition zone, and deep bedrock well was 3.6 feet (BC-4S), 3.1 feet (P1I), and 1.2 feet (BC-4D), respectively (table 12). Of all observation wells surrounding the pumping well, P6I and P6S to the northeast responded first to pumping (fig. 39), even though four wells were in closer proximity to the pumping well (table 11; fig. 38A). Four outcrops within 1000 feet of the test area exhibit a NE foliation strike (perpendicular to Boyd Branch) with near vertical dip angles (appendix 1a). Drawdown in wells parallel to foliation strike generally are larger and occur more quickly (for example, in P6S and P6I) than in other nearby wells (fig. 39). The next wells to respond to pumping were the nearby transition zone wells P5I and P1I, followed by the nearest to farthest shallow wells BC-4S, P5S, and BC-1S (fig. 39). Drawdown at P1S and P1I and P5S and P5I (positioned nearly perpendicular to foliation strike, fig. 38A) occurred more slowly and were less pronounced than at P6S and P6I (fig. 39; table 12) supporting the concept that preferential flow occurs parallel to foliation strike.

Drawdowns in clustered wells were compared at various times during the pumping test to evaluate how freely connected the upper regolith (saprolite) was with the lower regolith (transition zone). At P1, drawdown was 0.2 to 0.4 feet greater in the transition zone well (P1I) than in the saprolite well (P1S) at each observed time (table 12 and fig. 40). This suggests vertical stratification between the two open intervals. This effect also was observed at P5, where drawdown was 0.2 to 0.5 feet greater in the transition zone well P5I than in the saprolite well P5S for the first 10 hours of the test. Nearby transition zone wells generally responded to pumping effects from BC-4I more quickly than did the saprolite wells. The approximate lateral extent of influence due to pumping well BC-4I at 20 gpm over the 72-hour test is shown in fig. 41.

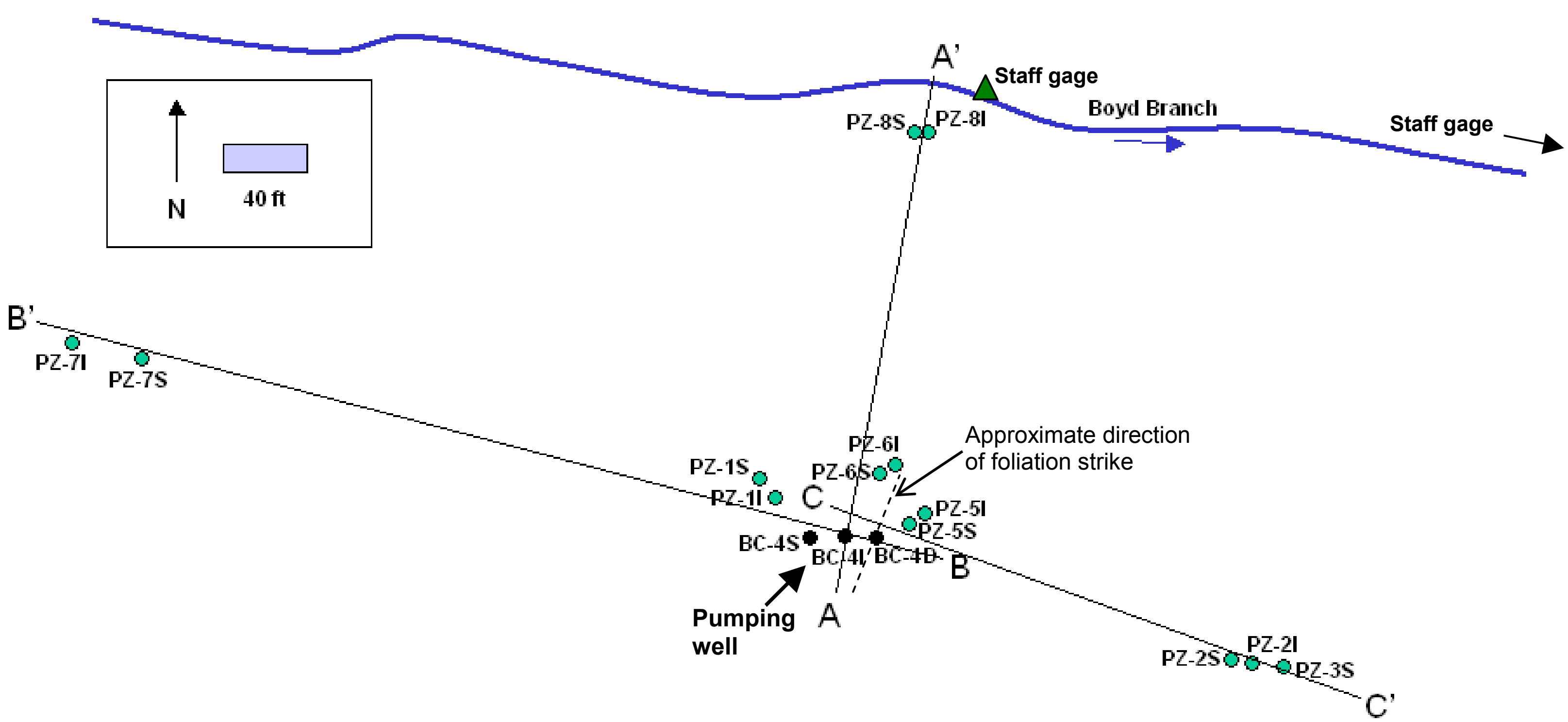

Figure 38A. Plan view of selected observation wells measured during 72-hour aquifer pumping test, Bent Creek Research Station, North Carolina.

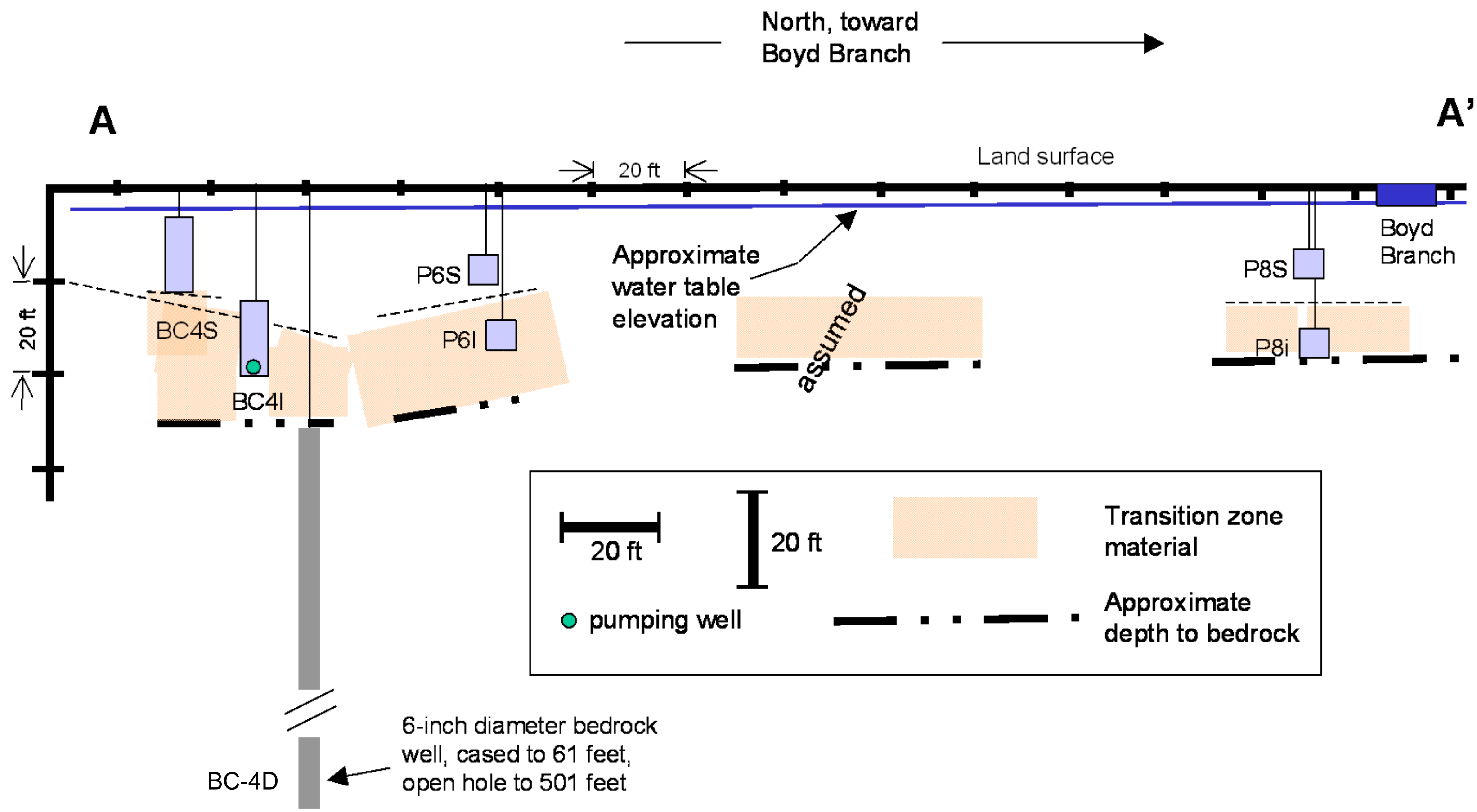

Figure 38B. Cross section A-A' showing selected wells screened in regolith, Bent Creek Research Station, North Carolina.

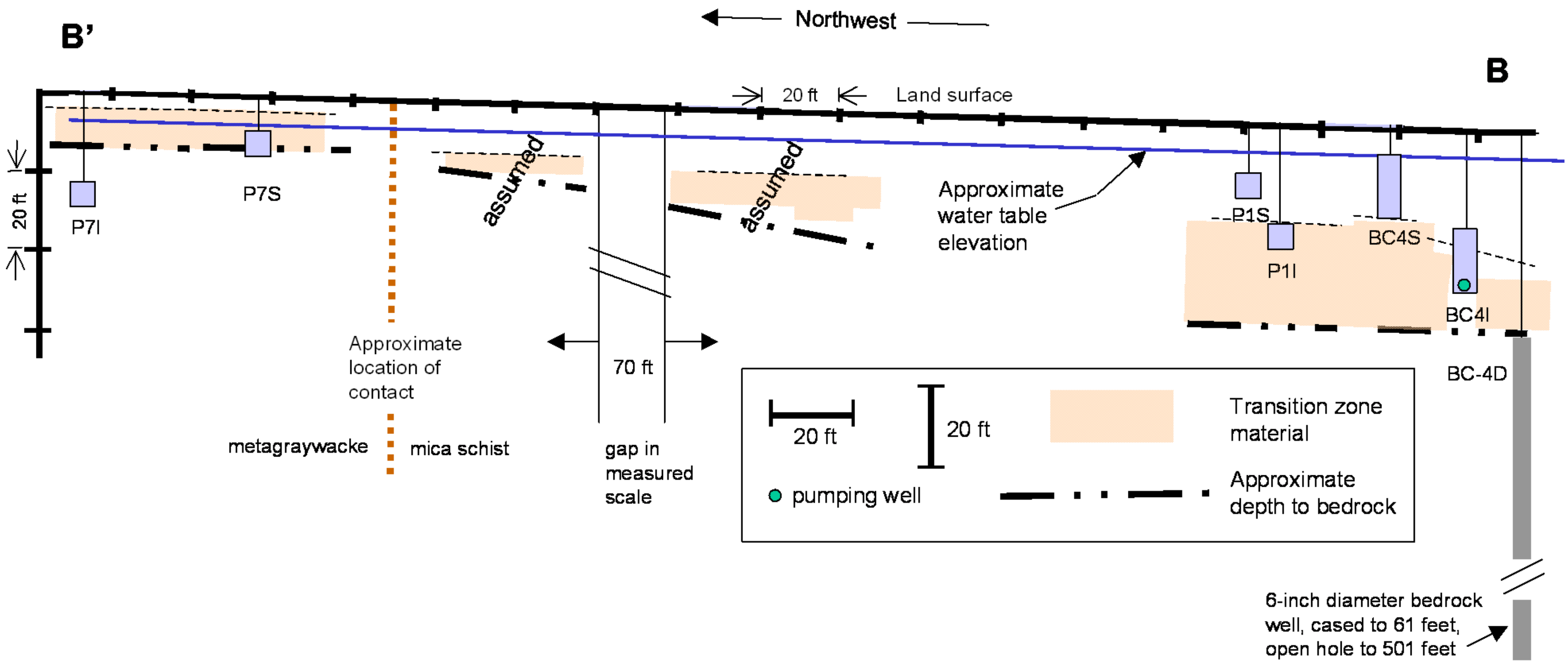

Figure 38C. Cross-section B'-B showing selected wells screened in regolith, Bent Creek Research Station, North Carolina.

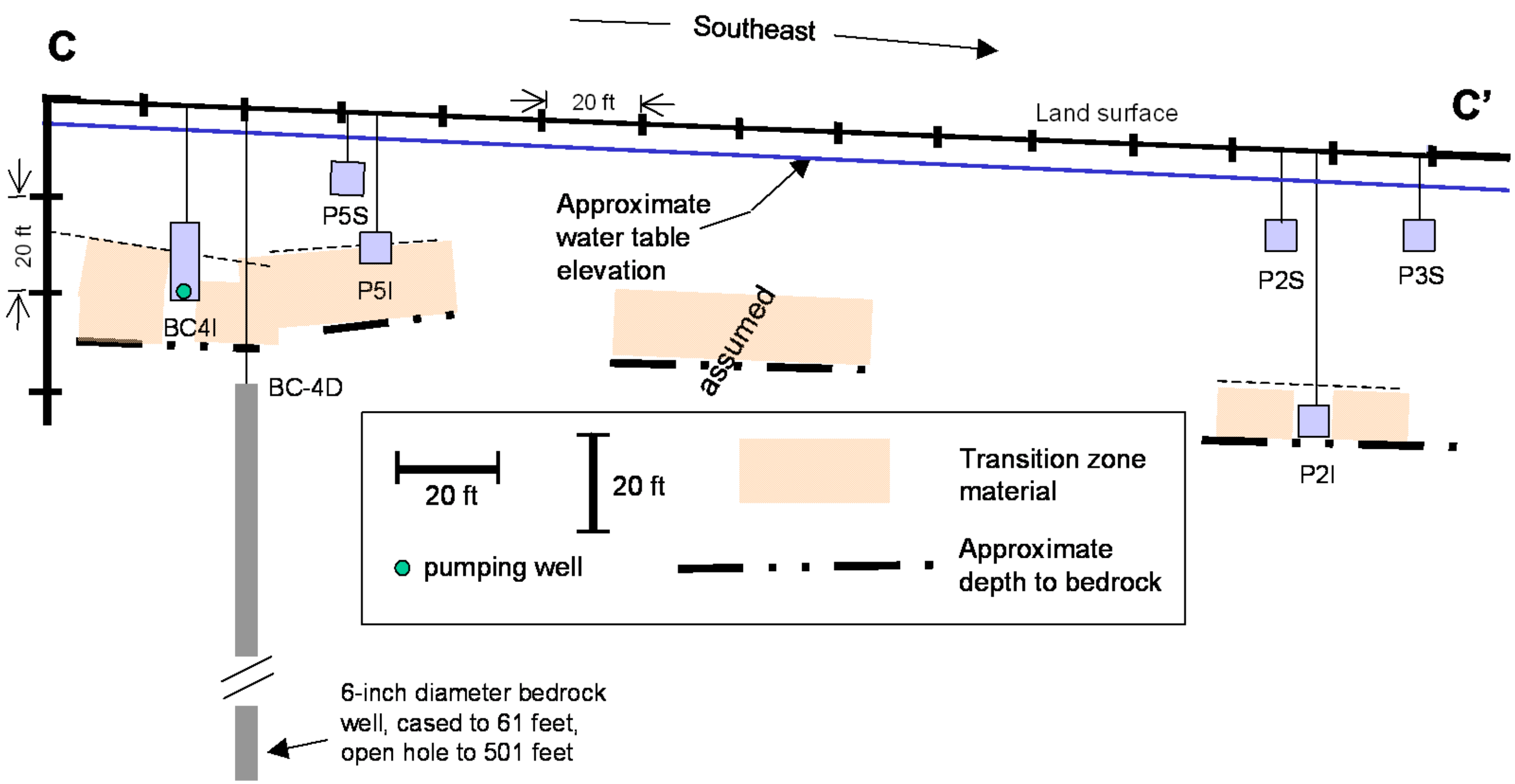

Figure 38D. Cross section C-C' showing selected wells screened in regolith, Bent Creek Research Station, North Carolina.

Table 11. Position, depth, and screen information for observation wells measured during aquifer pumping test conducted at lower regolith well BC-4I, Bent Creek Research Station, North Carolina.

Observation well	General orientation from pumping well	Distance from pumping well, in feet	Depth below land surface to top of casing, in feet	Screen length, in feet	Well diameter, in inches	Open to upper or lower portion of regolith
BC-4I (pumping well)	not applicable	0	26	15	4	lower
BC-4S	NW	18	7	15	4	upper
BC-4D	SE	18		open hole to 500	6.25	not applicable
P1S	NW	54	12	5	2	upper
P1I	NW	45	25	5	2	lower
P5S	E	32	12	5	2	upper
P5I	E	38	24	5	2	lower
P6S	NE	45	17	5	2	upper
P6I	NE	48	29	5	2	lower
P8S	NE	222	15	5	2	upper
P8I	NE	222	29	5	2	lower
P7S	N-NW	369	8.5	5	2	upper
P7I	N-NW	411	20	5	2	lower
P2S	SE	220	17	5	2	upper
P2I	SE	226	54	5	2	lower
P3S	SE	247	17	5	2	upper
P4S	SE	708	12	5	2	upper
P4I	SE	714	25	5	2	lower
BC-5S	NW	~1000	9	15	4	upper
BC-5I	NW	~1000	32	15	4	lower

Table 12. Drawdown in relation to time in observation wells measured during aquifer pumping test conducted at lower regolith well BC-4I, Bent Creek Research Station, October 11 to 14, 2004.

	Drawdown, in feet					
Well	2 min	10 min	30 min	1 hr	10 hrs	72 hrs
BC-4I	1.8	2.6	3.1	3.4	4.2	5.2
BC-4S	nc	0.4	1.1	1.5	2.5	3.6
BC-4D	nc	nc	nc	0.1	0.8	1.2
P1S	nc	0.2	0.6	0.9	1.6	2.8
P1I	nc	0.4	0.8	1.1	2	3.1
P5S	nc	0.3	0.8	1.2	2.1	3.4
P5I	0.1	0.7	1.2	1.5	2.1	2.9
P6S	0.3	1.2	1.7	2.1	2.9	4.0
P6I	0.4	1.2	1.8	2.1	2.9	3.9
P8S	nc	nc	0.1	0.2	0.5	1.0
P8I	nc	nc	nc	nc	0.3	0.7
P2S	nc	nc	nc	nc	0.1	0.3
P2I	nc	nc	nc	nc	0.2	0.4
P3S	nc	nc	nc	nc	0.1	0.2
P7S	nc	nc	nc	nc	nc	0.1
P7I	nc	nc	nc	nc	nc	0.2
P4S	nc	nc	nc	nc	nc	nc
P4I	nc	nc	nc	nc	nc	nc
BC-5S	nc	nc	nc	nc	nc	nc
BC-5I	nc	nc	nc	nc	nc	nc
BC-5D	nc	nc	nc	nc	nc	nc

Background wells	2 min	10 min	30 min	1 hr	10 hrs	72 hrs
BC-3S	nc	nc	nc	nc	nc	nc
BC-3I	nc	nc	nc	nc	nc	nc
BC-3D	nc	nc	nc	nc	nc	nc
BC-7S	nc	nc	nc	nc	nc	nc
BC-7I	nc	nc	nc	nc	nc	nc
BC-7D	nc	nc	nc	nc	nc	nc

nc, no change

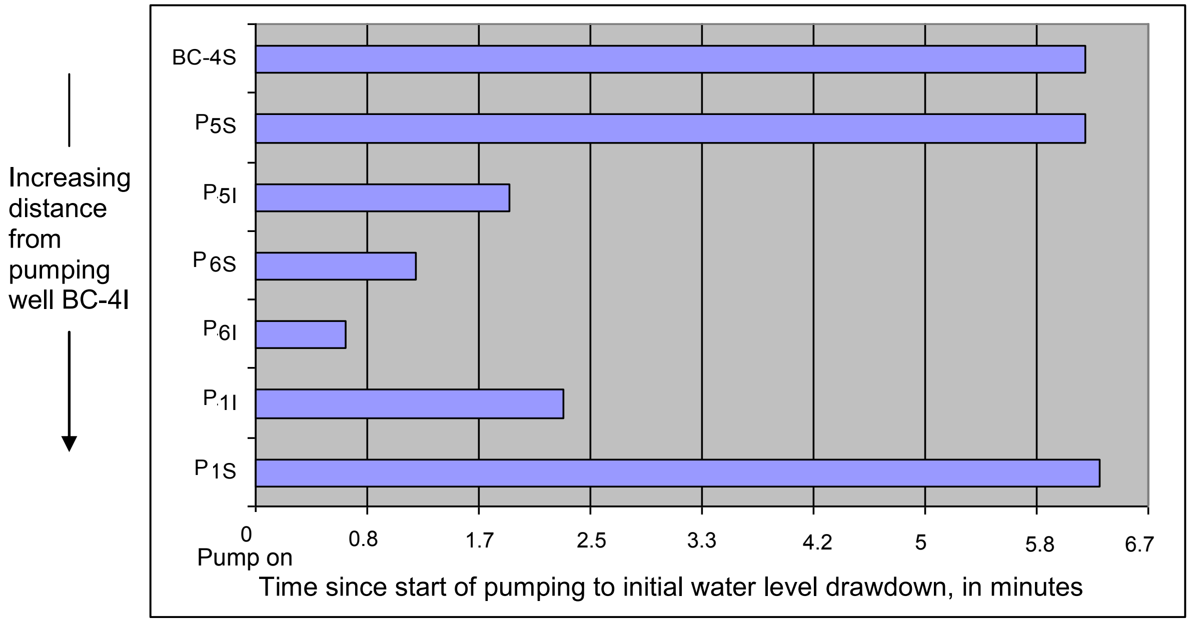

Figure. 39. Time to initial drawdown in observation wells in vicinity of pumping well BC-4I during aquifer test of October 11 to 14, 2004, Bent Creek Research Station, North Carolina.

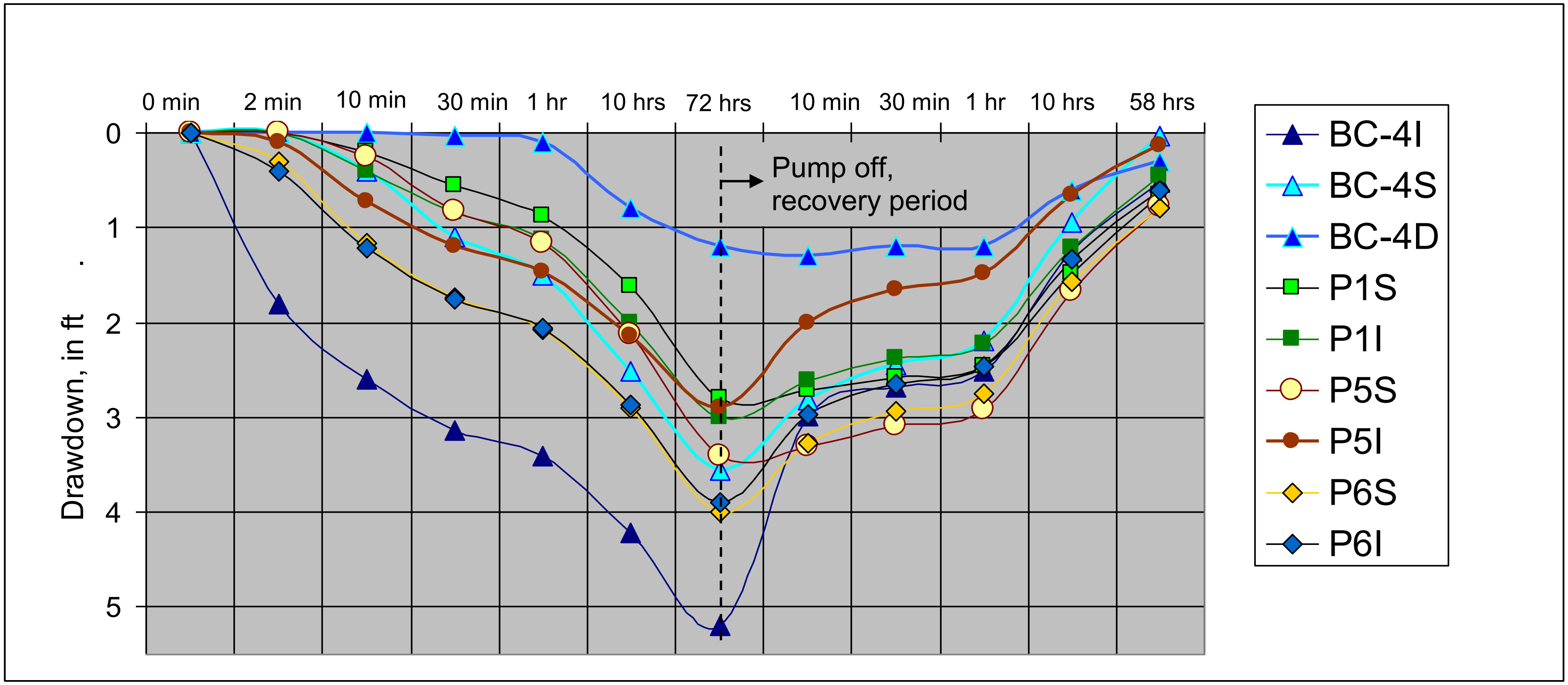

Figure 40. Drawdown and recovery in observation wells during 72-hour aquifer pumping test conducted at BC-4I, October 11 to 17, 2004, Bent Creek Research Station, North Carolina.

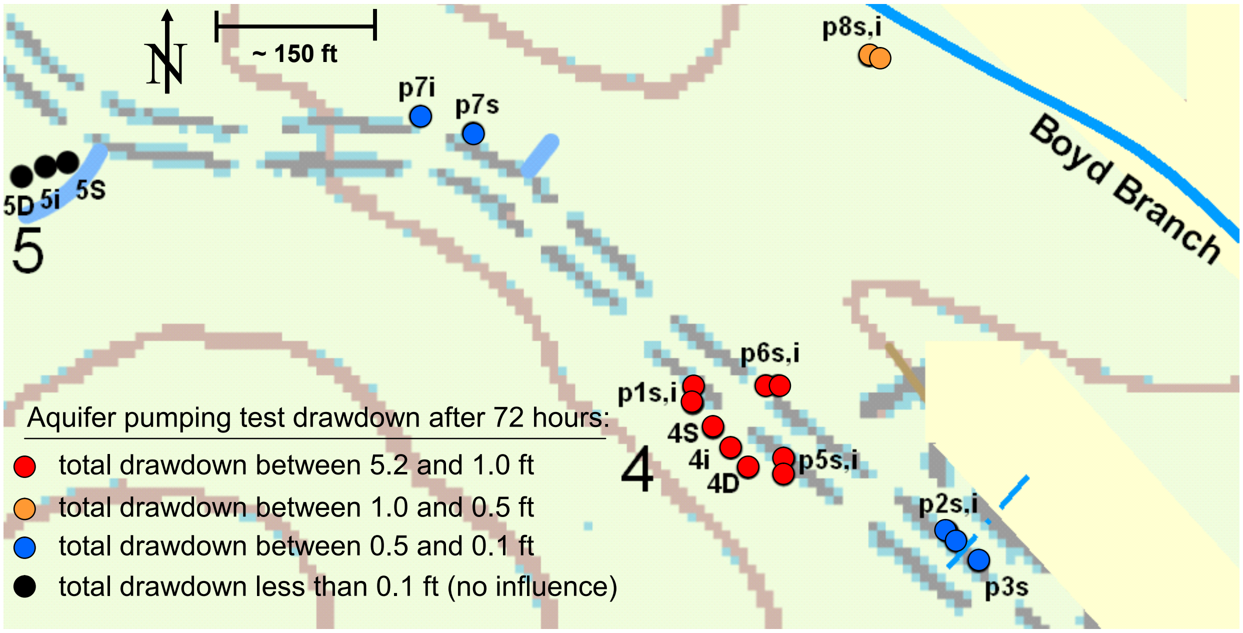

Figure 41. Influence due to pumping well BC-4I at 20 gallons per minute for 72 hours, October 11 to 14, 2004, Bent Creek Research Station, North Carolina.

Aquifer Response to 45-Hour Pumping in Bedrock

A second aquifer test was conducted in bedrock well BC-4D from June 20 to 22, 2006, to evaluate the hydraulic connection between the deeper, fractured rock flow system and the shallow regolith flow system. BC-4D, an open-hole bedrock well, was pumped at a relatively constant flow rate of about 4 gpm for 45 hours (fig. 42), and water levels were measured in wells and piezometers in the upper regolith, lower regolith, and bedrock in the vicinity. Total drawdown in BC-4D after just over 45 hours was 45.6 ft. The pump was placed at a depth slightly below two primary, water producing fractures observed on OTV logs for BC-4D at 105 feet bls.

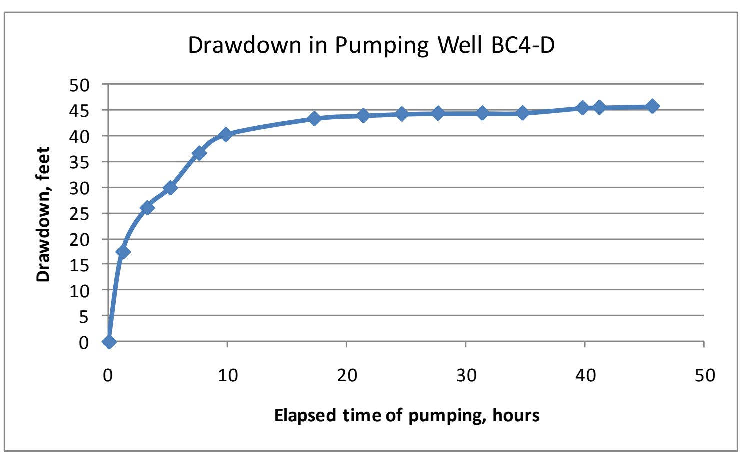

Figure 42. Drawdown in bedrock pumping well BC-4D during 45-hour aquifer test.

Only a minor, diffuse hydraulic connection was observed between the pumped portion of the flow system (fractured bedrock) and the overlying regolith. Drawdowns in regolith wells generally were modest and sluggish. The pumped bedrock well BC-4D was not hydraulically connected to bedrock wells located about 1000 feet upgradient (BC-5D) and 1500 feet downgradient (BC-3D). Observation wells with the greatest total drawdown were P5I (0.55 ft), P2I (0.49 ft), P5S (0.43 ft), BC-4I (0.31 ft), P2S (0.3 ft), P6I (0.3 ft), P6S (0.28 ft), BC-4S (0.24 ft), P1I (0.23 ft), P1S (0.21 ft), P3S (0.19 ft), P8I (0.12 ft), and P8S (0.12 ft). All other wells had drawdowns of less than 0.1 feet over the 45 hours, and these values were interpreted as a minor seasonal water level trend and not due to pumping at BC-4D.

The fractures that produce the 4 gpm yield in BC-4D (inferred to be at 105 ft) may be better connected to regolith beyond the area of observation or may be hydraulically connected to Boyd Branch located about 200 feet to the east. In other words, the well may draw water from a source not measured during the aquifer test (no attempt was made to measure flow rates in Boyd Branch during the aquifer test). The fractures at 105 feet contained 20 to 40 year old groundwater (estimated by age dating analysis) during a sampling event using an inflatable packer sampling system. As results from other REP investigations in the Piedmont-Mountains make clear, hydraulic connectivity between bedrock and regolith and between neighboring bedrock wells varies from site to site, depending on a host of local hydrogeologic factors (Pippin and others, 2008; Chapman and others, 2005; oral communications, S. Wang, J. Pippin, and L. Skidmore, NCDENR, April 21, 2008).

Age

Groundwater samples were collected and analyzed for CFCs (and tritium-helium in selected samples) in clustered regolith and bedrock wells at BC-1, BC-2, BC-3, BC-4, BC-5, and BC-7 at various dates in 2004 and 2005. For quality control, halon had been mixed with compressed air during the original air-rotary well drilling activities to serve as a tracer that would indicate whether or not modern air containing CFC's was introduced to the groundwater during well installation. If halon was not present in the groundwater then the sample generally was considered representative of the natural flow system and an age was estimated. Sampling and analysis procedures are described at the U.S. Geological Survey's Reston Chlorofluorocarbon Laboratory in Reston, Virginia (USGS website http://water.usgs.gov/lab/cfc/). Both the mean (piston-flow) CFC ages and tritium/helium ages (used to determine the youngest component of groundwater) were estimated where possible.

Groundwater collected from a well was comprised of waters that traveled along different flow paths and, in some cases, from different source areas. This was especially true in the case of bedrock wells, which often tap and draw water from numerous fractures that may be connected to different source areas located at varying distances from the well. Because of the complex nature of the three-dimensional flow system, wells inherently drew water that is a composite of various source waters. Thus, a range of ages were expected in a given sample of groundwater drawn from bedrock wells.

The apparent CFC-derived age of groundwater in bedrock wells ranged from about 20 to 50 years (written communication, M. Chapman, October 2, 2008)(fig. 43 and table 13). One exception to this was at well BC-7D in which 40-year old water was mixed with younger, modern water, suggesting that at least some local recharge (modern water) occurred near the well head. The apparent CFC-derived age of groundwater in upper regolith saprolite wells (screened across the water table at depths of 5 to 30 feet bls) ranged from 1 to 26 years, and the tritium/helium-derived age ranged from 2 to 3 years. The apparent CFC-derived age of groundwater in lower regolith transition zone wells (screened at depths of 8 to 53 feet bls) ranged from about 1 to 30 years, and the single tritium/helium-derived age was 14 years. The youngest component of groundwater derived from tritium/helium analyses generally was unavailable for bedrock wells.

Groundwater age is dependent on flow path length and properties and, in the case of bedrock wells, the connectedness of the producing fracture to the overlying regolith storage. To illustrate, groundwater in bedrock wells in downslope, discharge areas (BC-1D and BC-2D, with median age about 42 years)(fig. 4) tended to be older than groundwater in bedrock wells in mid- or upslope, recharge areas with expected shorter median flow paths (BC-4D and BC-7D, with median age about 26 years)(table 13). At each sampled well cluster location, groundwater was older in the bedrock well than in its corresponding overlying regolith well.

Two-decade old groundwater was identified in relatively shallow discharge-area regolith wells BC-1S, -1I, and -2I, reflecting a longer flow path component of water and potentially upward mixing of older water from deeper bedrock fractures. The oldest estimated age of water in BC-1S, -1I, and -2I is

25, 25, and 19 years, respectively (table 13 and fig. 43). The youngest estimated component of water using tritium analysis in BC-1S is 2 years, reflecting a mixture of very young local recharge, potentially from surface-water exchange, near the well head. This finding corroborates the results of groundwater temperature recordings (section titled 'Seasonal and Storm-Induced Groundwater Temperature Fluctuations) that suggest lateral stream mixing (young water) and upwelling (somewhat older water) at this location. Tritium analyses were not available for BC-1I and -2I.

Nearly two-decade old groundwater also was identified in the relatively shallow, mid-slope regolith well BC-7S (recharge area), again reflecting a longer flow path component of groundwater. While the well had a relatively shallow sample interval (screened opening from 10 to 25 feet bls), the sediments comprising the regolith flow system at this location were particularly tight (slug test K of 0.2 ft/day) which would help account for slow moving recharge. The youngest component age date from tritium analysis is 1 year, reflecting a mixture of very young local recharge.

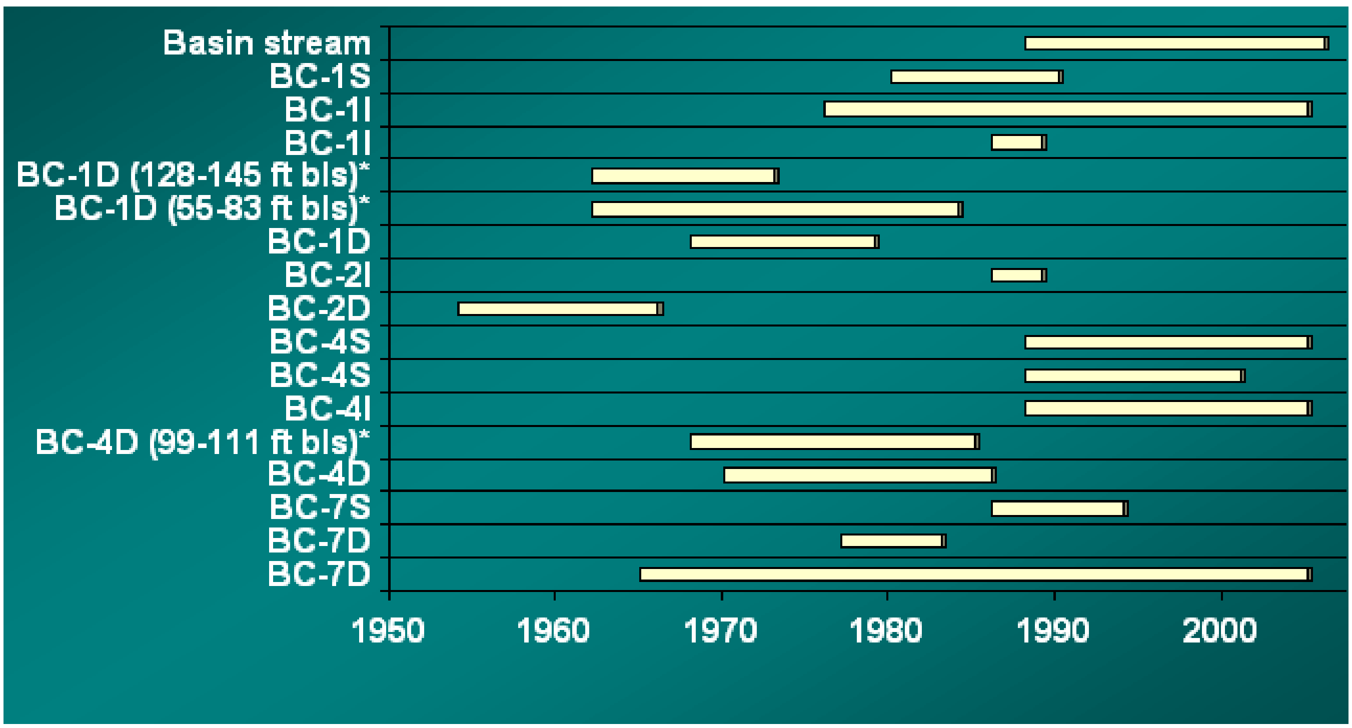

Figure 43. Mean age dates (chlorofluorocarbon piston-flow range) for stream and ground water at selected wells in the Bent Creek Research Station, North Carolina. Written communication, M. Chapman, October 2, 2008.

Table 13. Apparent age at time of sampling in 2005 of stream and ground water at selected locations, Bent Creek Research Station, North Carolina. Written communication, M. Chapman, October 2, 2008.

			Older component:	Youngest component:	
Sample location[a]	hydologic setting	Flow zone	Apparent age[b] using CFCs	Apparent age[c] using tritium-helium, +/- 1 yr	Estimated range of age at time of sampling, in yrs; older (and younger)
Basin stream		surface water	1988 to 2005		1 to 17
BC-1S	low lying, discharge area	upper regolith, alluvium & TZ	1980 to 1990	2003	15 to 25 (and 2)
BC-1I	low lying, discharge area	lower regolith, TZ	1976 to 2005		1 to 29
BC-1I	low lying, discharge area	lower regolith, TZ	1986 to 1989		16 to 19
BC-1D (128-145 ft bls)[d]	low lying, discharge area	bedrock	1962 to 1973		32 to 43
BC-1D (55-83 ft bls)[d]	low lying, discharge area	bedrock	1962 to 1984		21 to 43
BC-1D	low lying, discharge area	bedrock	1968 to 1979		26 to 37
BC-2I	low lying, discharge area	lower regolith, TZ	1986 to 1989		16 to 19
BC-2D	low lying, discharge area	bedrock	1954 to 1966		39 to 51
BC-4S	midslope, recharge area	upper regolith, saprolite	1988 to 2005		1 to 17
BC-4S	midslope, recharge area	upper regolith, saprolite	1988 to 2001		4 to 17
BC-4I	midslope, recharge area	lower regolith, TZ	1988 to 2005	1992	1 to 17 (and 13)
BC-4D (99-111 ft bls)[d]	midslope, recharge area	bedrock	1968-1985	1986	20 to 37 (and 19)
BC-4D	midslope, recharge area	bedrock	1970-1986		19 to 35
BC-7S	midslope, recharge area	upper regolith, saprolite	1986 to 1994	2004	11 to 19 (and 1)
BC-7D	midslope, recharge area	bedrock	1977 to 1983		22 to 28
BC-7D	midslope, recharge area	bedrock	1965 to 2005		1 to 40

[a] Age date samples collected in January 2005 and November 2005

[b] CFC-derived age estimated using piston flow model

[c] Helium/tritium-derived age of youngest ground water present in sample

[d] Sample obtained from specified interval using downhole inflatable packers

yr, year; ft bls, feet below land surface; TZ, transition zone

WATER QUALITY

Water quality samples were collected periodically between 2003 and 2007, and continuously (at well cluster BC-2) between February and June 2005, at the BCRS to characterize groundwater chemistry in a schist-gneiss rock type. The purpose of sampling was to (1) determine the groundwater "type" or geochemistry associated with the schist-gneiss rock type and compare this to the chemistry of regional groundwater; (2) evaluate changes in water quality with season; (3) compare the chemical signature from three depths of the groundwater flow system (upper regolith (saprolite), lower regolith (transition zone), and fractured bedrock); (4) evaluate potential differences in water quality in recharge and discharge areas; (5) evaluate changes in water quality in response to short-term rainfall events; (6) determine the presence or absence of naturally occurring and anthropogenic contaminants in a pristine mountain watershed; and (7) compare groundwater chemistry to the chemistry of the bedrock through which the groundwater flows.

Water quality samples were obtained from 4 streams, 6 well clusters (19 wells in all), and 2 water supply wells in a nearby sub-basin (Arbor-3 and Arbor-4) within the Bent Creek watershed (fig. 44). Samples were collected during three to seven sampling events that corresponded to a variety of seasonal and hydrologic conditions, including extreme low water levels during drought conditions (for example, June 12, 2006 and August 20, 2007) and somewhat higher water levels after the heavy rainfall during September 2004 (for example, November 1, 2004). Analyses included major ions, metals, nutrients, volatile and semi-volatile organics, physical and biological properties, and selected naturally occurring radionuclides. In addition, continuous hourly measurements of pH, DO, temperature, and SC were made during the period between August 2004 and December 2005 at wells BC-2S, -2I, and -2D, and at the stream gage in Boyd Branch, adjacent to well cluster BC-2 (B. Huffman, written communication, September 2, 2008).

Unless otherwise noted, evaluations and discussion are based on a selected representative value (typically the median value) at a given well or stream site as determined from all values measured at that location over multiple sample dates. Previously published (Huffman and others, 2006) Piper trilinear diagrams (Piper, 1953) displaying dominant cations and anions developed from well and stream water chemistry data are presented for comparative purposes. Stiff diagrams (Stiff, 1951) are presented for the current dataset[14]. The data also were compared to published regional datasets, including the study by Trapp (1970) with 16 bedrock wells in Buncombe County, the data analyzed by the North Carolina Public Health Lab (NCDHHS, 2008, webpage http://slph.ncpublichealth.com/EnvironmentalSciences/inorganic/, accessed December 22, 2008) with 56 to 532 (depending on the constituent) bedrock wells in Buncombe County, and the regional analysis by Briel (1997) with 322 to 558 (depending on the constituent) bedrock wells across the Blue Ridge Province.

The quality of water was related in large part to the concentration and types of dissolved ions that it contained and was thus dependent upon the host rock through which it flowed. Water entering the groundwater system as recharge contains dissolved gasses from the atmosphere, soil, and organic matter (oxygen and carbon dioxide, for example) and, because this recharge water is typically acidic it acts as a mild solvent. As the acidic water moves through the groundwater system, it dissolves minerals such as the cations calcium, magnesium, sodium, and potassium in the soil and rock and, in the process, carbon dioxide is converted to the bicarbonate anion.

Older, deeper groundwater that traveled greater distances was usually more mineralized than younger, shallower groundwater (or surface water) that traveled shorter distances. Dissolved solids in groundwater with a relatively short residence time were, in some cases, too low for the overall groundwater composition to reflect effects of the dissolution of the rock formation. The groundwater composition also varied somewhat due to the heterogeneity of the rock formations. Water quality data analyzed in this study were consistent with this conceptual model.

Ground and surface water in the Bent Creek study area are of high quality. Concentrations of dissolved inorganic constituents typically are very low, as are SC, total organic carbon (TOC), fecal bacteria, nutrients, pesticides, herbicides, volatile and semi-volatile organic compounds, and naturally

[14] To generate the Stiff diagrams, values reported as below method detection limits were assigned a value of one half the detection limit.

occurring uranium, radium-226, and arsenic. These findings are consistent with regional findings in many pristine settings (Briel, 1997; Trapp, 1970).

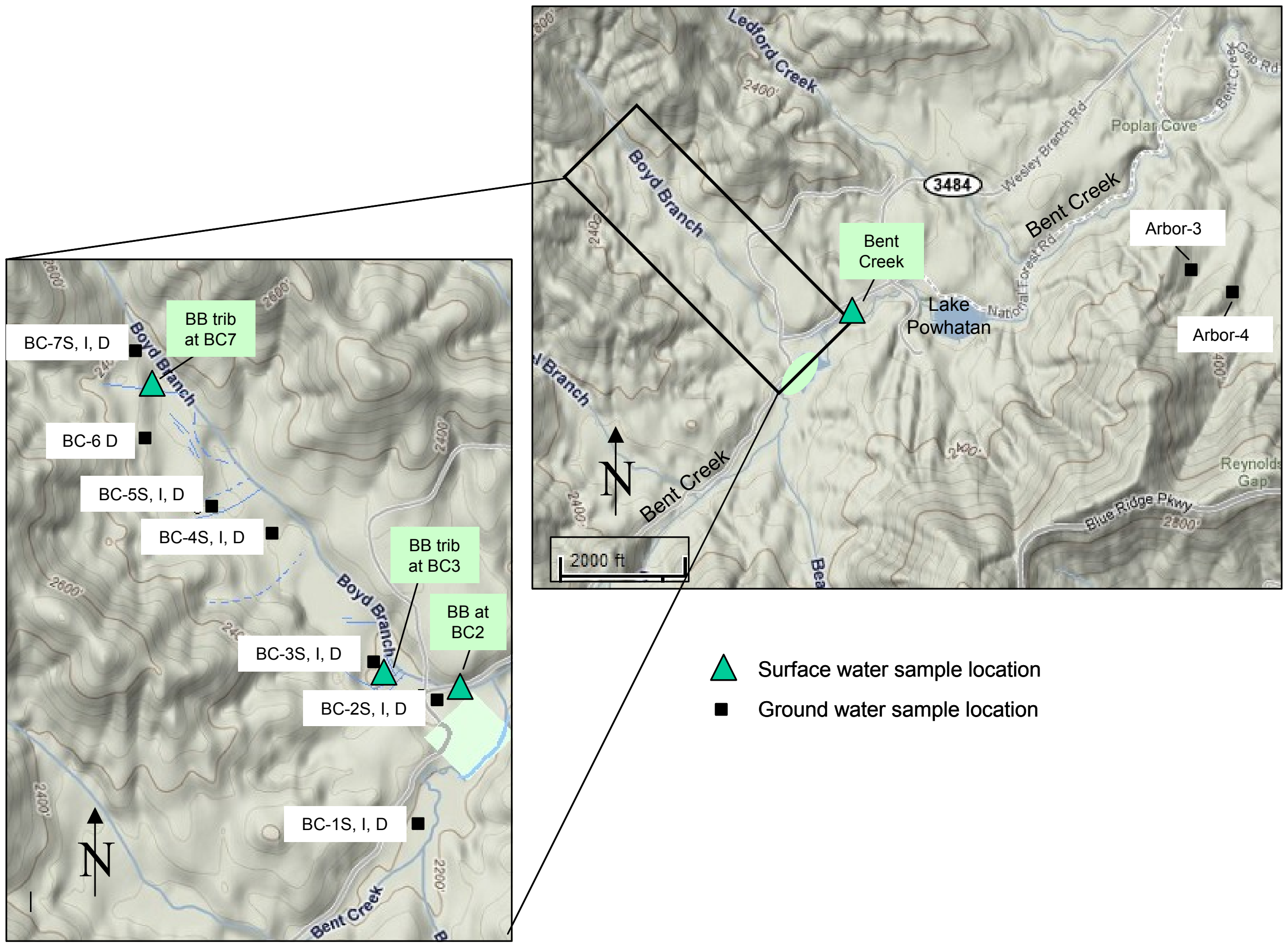

Figure 44. Location of ground and surface water quality sample locations at Bent Creek Research Station, North Carolina.

Groundwater Type and Comparison to Regional Water Quality

Based on major anion (bicarbonate, chloride, and sulfate) and cation (calcium, sodium, magnesium, and potassium) concentrations observed in sample water from seven bedrock wells, groundwater in the bedrock flow system in the study area is considered a calcium bicarbonate type. A Stiff diagram (fig. 45) shows the major ion milliequivalent results from a June 2006 sampling event, as analyzed by the NCDWQ laboratory. A Piper diagram (fig. 46) shows major ion results from an April 2003 sampling event, as analyzed by the USGS National Water Quality laboratory in Denver and published by Huffman and others (2005). These findings are consistent with those published by Trapp (1970) in which a Type II groundwater (calcium-bicarbonate) was identified for wells in similar rocks in Buncombe County. Trapp noted that the Type II water was associated with garnet-muscovite schist and biotite gneiss, both of which are predominant rock types in the study area. Tables 14 and 15 show data used to evaluate water quality in the study area. Table 16 shows whole-rock chemistry oxide analyses for rock samples obtained from core holes BC-1, BC-3, and BC-7.

Bicarbonate was the principal anion in the study area bedrock well water (fig. 45 and 46), with concentrations ranging from 15 to 57 mg/L (median = 44 mg/L) (tables 14 and 15). Dissolved bicarbonate is produced by the conversion of carbon dioxide during the dissolution of cations during the rock weathering process. Sulfate concentrations were the second most dominant anion, with concentrations ranging from less than 4 to 26 mg/L (median = 10 mg/L). Chloride concentrations ranged from less than 1 to 3.7 mg/L (median = less than 1 mg/L), with most samples near or below the detection limit of 1 mg/L. By comparison, Trapp (1970) observed median concentrations of bicarbonate, sulfate, and chloride of 54, 11, and 2.2 mg/L, respectively, in 16 bedrock wells in Buncombe County (table 14).

Calcium was the principal cation in study area bedrock well water (figs. 45 and 46), with concentrations ranging from 3.1 to 23 mg/L (median = 18 mg/L) (table 14 and 15). The source of dissolved calcium is dissolution of rock that contains calcium-bearing minerals such as plagioclase feldspar, amphibole, and garnet. For example, migmatite and biotite gneiss/metagraywacke rocks are very common within the study area and both contain significant amounts of plagioclase feldspar (32 percent and 32 to 42 percent, respectively (Merschat and Carter, 2002)). Amphibolite, though less common, did appear within some intervals of rock core, and contained plagioclase feldspar at amounts from trace to 38 percent (Merschat and Carter, 2002). Garnet is a very common accessory mineral in the study area in both the schist and gneiss.

Sodium generally was the second most dominant cation, with concentrations ranging from 2.8 to 20 mg/L (median = 3.7 mg/L) (table 14). Possible sodium sources include potassium feldspar (one rock sample showed 28 percent) and plagioclase feldspars. Magnesium concentrations ranged from 0.4 to 3.3 mg/L (median = 1.3 mg/L), and potassium concentrations ranged from 0.8 to 4.3 mg/L (median = 2 mg/L). Generally, the migmatite and biotite gneiss/metagraywacke rocks in the study area contain significantly higher percentages of calcium oxide and sodium oxide than schist rocks (Merschat and Carter, 2002; table 16), and the schist rocks contain significantly higher iron oxide content (Merschat and Carter, 2002) and the iron sulfide mineral pyrrhotite (A. Merschat, written communication, August 1, 2003) than the migmatite and metagraywacke. Pyrrhotite and other iron and sulfur rich minerals weather to produce dissolved iron and sulfate. The iron can then oxidize and precipitate out of solution to produce orange stains on rocks and fracture openings. The solution from pyrrhotite is acidic, which allows for further dissolution of calcium and other ions from the host rock. So, depending on the geochemical conditions of the groundwater and the lithology of the host rock through which groundwater passes, higher calcium, sodium, and sulfate concentrations are possible, and some mixture of the three is the result.

To determine how groundwater quality in the study area compares with regional water quality, summary well data were compiled for study wells, Buncombe County (16 well samples from Trapp, 1970; 56 to 532 well samples, depending on constituent, from NCDHHS, 2008, webpage http://slph.ncpublichealth.com/EnvironmentalSciences/inorganic/ accessed December 22, 2008), and the Blue Ridge Province (322 to 558 well samples, depending on constituent, from Briel, 1997) (table 14). Data summaries also were compiled for three adjacent counties (Henderson, Madison, and Transylvania) (Trapp, 1970) (table 14).

Levels of constituents in study area well water generally were comparable to levels reported for Buncombe County and Blue Ridge Province wells (table 14). An exception to this was elevated pH, and, to a lesser extent, calcium in 4 of 7 study wells (table 15). These highly buffered wells - BC-2D, -3D, -4D, and -7D - had a pH range of 8.6 to 7.9 (median = 8.1) and a calcium range of 23 to 18 mg/L (median = 21 mg/L) (table 15). In contrast, the 68th and 95th percentiles for pH in the Buncombe County NCDHHS dataset (n = 524) were 7.6 and 8.2 respectively, and for the Buncombe County Trapp dataset (n = 16) were 7.6 and 8.6, respectively. For calcium, the 68th and 95th percentiles in the NCDHHS dataset (n = 531) were 27 mg/L and 39 mg/L, respectively, and the 68th and 95th percentiles in the Trapp dataset (n = 16) were 22 mg/L and 32 mg/L, respectively. Comparing the datasets of bedrock well chemistry for the study area, Buncombe County (NCDHHS, 2008), Buncombe County (Trapp, 1970), and Blue Ridge Province (Briel, 1997), median values of pH were 7.9, 7, 6.8, and 6.6, respectively; SC were 122, not determined, 129, and 103 uS/cm; bicarbonate were 48, not determined, 54, and 32 mg/L; chloride were <1, <5, 2.2, and 2.1 mg/L; sulfate were 10, 7, 5.4, and 5 mg/L; calcium were 18, 11.2, 11, and 8.3 mg/L; magnesium were 1.3, 2.5, 3, and 2.5 mg/L; potassium were 2, not determined, 2.2, and 1.2 mg/L; sodium were 3.7, 6, 5.3, and 5 mg/L; and silica were 17, not determined, 23, and 16 mg/L (table 14).

Only three study area well locations, BC-1D (0.84 mg/L), BC-3D (0.39 mg/L), and BC-5D (0.69 mg/L), had median dissolved iron concentrations above the detection limit of 0.05 mg/L (table 15). Dissolved manganese concentrations were low in all locations and ranged from less than the detection limit of 0.01 mg/L to 0.058 mg/L. Dissolved lead and cyanide were below their respective detection limits of 0.01 and 0.02 mg/L in all sampled locations. Similarly, all other measured dissolved minor metals were at relatively low concentrations, typically at or near their respective detection limits (table 15).

Changes in Groundwater Quality with Season

In general, water quality at a given well location did not vary significantly across different sampling dates and seasons. A typical example of this is provided in fig. 47, which shows relatively consistent concentrations of selected water quality parameters in bedrock well BC-4D measured during several sampling events. These findings suggest that water quality in this setting was not significantly dependent upon seasonal changes. Typically, this was also the case at other well locations. Where they exist, differences in water quality between events may be due to short-term rainfall events (flushing influences), seasonal hydrologic variation, laboratory precision, and (or) slight changes in pump depth during sampling.

Changes in Groundwater Quality with Depth and Topographic Setting

To compare water chemistry at different depths of the groundwater flow system, water samples were collected from six well clusters drilled in the upper regolith (saprolite, water table wells), lower regolith (transition zone), and open-hole bedrock; four streams also were sampled (fig. 44). In general, groundwater in the upper and lower regolith was slightly acidic due to humic acids in soil and to chemical and mechanical weathering of iron-sulfide bearing minerals in parent rock. The shallow groundwater thus acted as a weak acid that tended to dissolve metals in the soil and rock as it moved into and through the deeper, fractured bedrock flow system. The result was an increase in dissolved ions, SC, and pH, and a decrease in DO in bedrock wells. This is typical of other groundwater research stations in the Piedmont-Mountains (Pippin and others, 2008, Chapman and others, 2005) and suggests that most of the DO contained in rain water that seeps into the soil is consumed in the microbially mediated oxidation of organic matter as the water moves downward through the regolith.

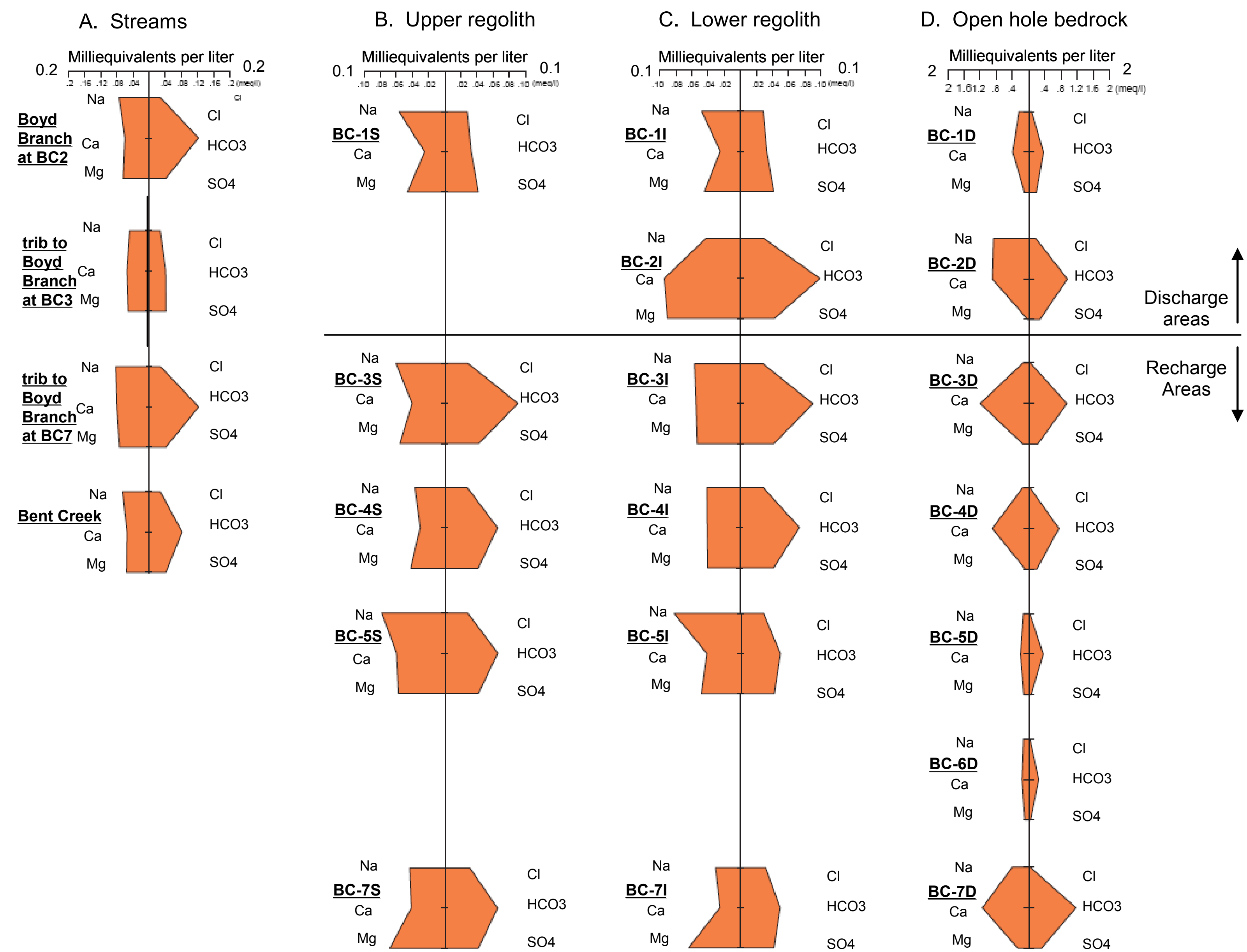

Figure 45. Stiff diagrams showing major ion milliequivalents in water samples collected from (A) streams (0 to 0.2 scale), (B) upper regolith wells (0 to 0.1 scale), (C) lower regolith wells (0 to 0.1 scale), and (D) open-hole bedrock wells (0 to 2 scale), June 2006, Bent Creek Research Station, North Carolina.

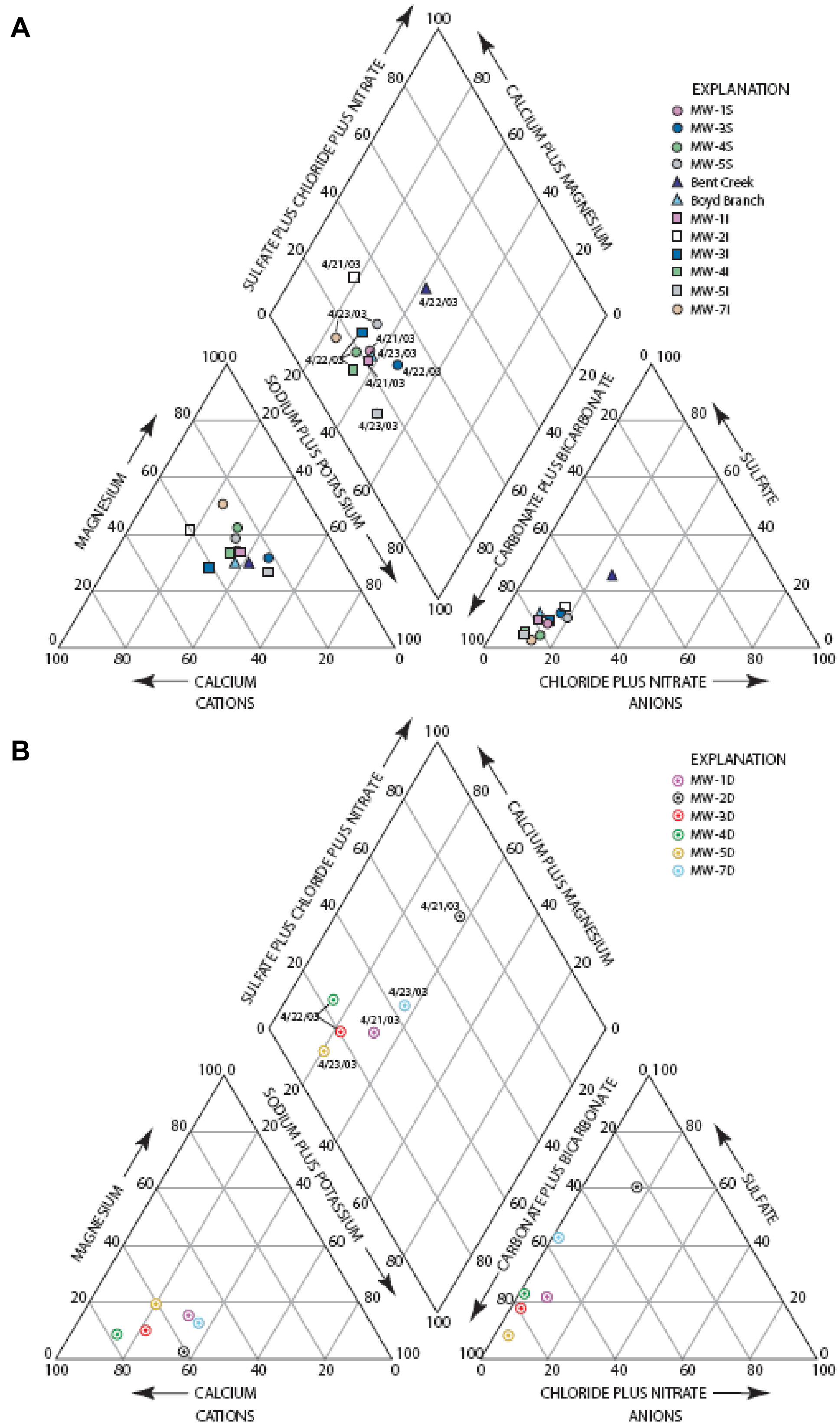

Figure 46. Trilinear Piper diagrams showing water chemistry data from April 2003, at (A) regolith wells and stream sites, and (B) open hole bedrock wells, Bent Creek Research Station, North Carolina, from Huffman and others (2006).

Table 14. Statistical summaries of water quality results for regional studies and sample locations at the Bent Creek Research Station, North Carolina.

BCRS sample locations and regional datasets	pH	SC uS/cm	DO mg/L	TDS mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Si mg/L
Saprolite wells[a]												
minimum	5.1	14	3.4	15	4	<1	<2	0.6	0.5	0.6	0.8	6.9
maximum	5.5	24	8.2	24	7	1	<2	1	0.7	1.2	1.9	11.5
average	5.4	18	6.1	19	5	<1	<2	0.8	0.6	0.8	1.3	8.9
median	**5.4**	**17**	**6**	**19**	**5**	**<1**	**<2**	**0.7**	**0.7**	**0.8**	**1.2**	**8.5**
Transition zone wells												
minimum	5.3	12	5.4	14	3	<1	<2	0.5	0.5	0.3	0.7	7
maximum	5.7	19	9.0	26	7	1.1	<2	1.1	1.5	0.8	2.0	12.0
average	5.5	16	6.9	21	5	<1	<2	0.8	0.7	0.5	1.2	8.8
median	**5.5**	**16**	**7.0**	**22**	**6**	**<1**	**<2**	**0.8**	**0.6**	**0.6**	**1.2**	**8.9**
Bedrock wells												
minimum	6.2	46	0.1	38	15	<1	<4	3.1	0.4	0.8	2.8	10
maximum	8.6	214	6.9	140	57	3.7	26	23	3.3	4.3	20	23
average	7.5	114	1.6	81	37	1.2	10.6	13.9	1.5	2.2	6.7	17.4
median	**7.9**	**122**	**0.2**	**82**	**48**	**<1**	**10**	**18**	**1.3**	**2**	**3.7**	**17**
Surface water												
minimum	6.6	15	7.8	23	5	<1	<2	0.9	0.6	0.6	1.1	8
maximum	6.9	22	9.4	28	7	2.5	<2	1.6	0.9	0.8	1.8	13
average	6.8	18	8.6	26	6	1	<2	1.2	0.7	0.7	1.5	10.6
median	**6.8**	**18**	**8.7**	**26**	**6**	**<1**	**<2**	**1.2**	**0.7**	**0.7**	**1.5**	**10.7**
Regional data												
NCDHHS, 2008[b] (n = 56 to 532)	7					<5	7	11.2	2.5		6	
Trapp, 1970[c] (4 counties, n = 62)	6.8	129			54	2.2	5.4	11	3	2.2	5.3	23
Buncombe Co, n = 16	6.8	129			54	2.2	5.4	11	3	2.2	5.3	23
Henderson Co, n = 22	6.3	45			26	1.2	0.2	2.8	1.2	0.9	3.7	19
Transylvania Co, n = 12	6.4	18			21	1.1	0.4	3	0.6	0.9	4	18
Madison Co, n = 12	6.3	125			53	2	3	10	4.9	2.3	4.9	32
Briel, 1997[d] (n = 322 to 558)	6.6	103	6.2	73	32	2.1	5	8.3	2.5	1.2	5	16

[a] Saprolite well BC-2S was not included in statistical analyses due to potential grout contamination; [b] Data obtained from bedrock drinking wells in Buncombe Co, with n = 56 to 532, depending on constituent (n = 14 for DO); [c] Data obtained from drilled bedrock drinking wells in Buncombe, Henderson, Transylvania, and Madison Counties, with n = 62; [d] Data obtained from bedrock drinking wells in the Blue Ridge Province, with n = 322 to 558, depending on constituent. Abbreviations: SC, specific conductance; DO, dissolved oxygen; Alk, alkalinity; TDS, total dissolved solids; HCO_3, bicarbonate; Cl, chloride; SO_4, sulfate; Ca, calcium; mg, magnesium; K, potassium; Na, sodium; Si, silica; mg/L, milligrams per liter; BCRS, Bent Creek Research Station.

Table 15. Median water quality results for locations within the Bent Creek Research Station, North Carolina, 2003 to 2007, and data compiled from regional studies.

BCRS sample locations and regional datasets	pH	SC uS/cm	DO mg/L	TDS mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Si mg/L
BC-1S	5.3	16	5.4	22	6	<1	<2	0.8	0.5	0.3	1.2	10
BC-1i	5.5	14	7	20	5	<1	<2	0.8	0.5	0.3	1.1	8.9
BC-1D	6.8	71	0.2	64	21	1.8	8.1	7.5	1.3	0.8	5.6	23
BC-2S[a]	6	200		380	78	3.7	18	25	8.3	1.8	2.1	6
BC-2i	5.5	19	6	24	6	1	<2	0.7	1.5	0.4	1.2	7
BC-2D	8.6	214	0.1	140	48	<7.4	26	18	0.4	1.1	20	22
BC-3S	5.1	15	6.3	24	5	<1	<2	0.8	0.7	0.6	1.4	10
BC-3i	5.7	17	7.8	24	6	<1	<2	1.1	0.6	0.8	1.3	9.2
BC-3D	8.3	136	0.2	100	57	0.8	11	23	1.7	2.5	3.2	17
BC-4S	5.5	14	8.2	15	4	<1	<2	0.6	0.5	0.7	0.8	7
BC-4i	5.6	13	9	16	4	<1	<2	0.7	0.5	0.8	0.9	7.6
BC-4D	7.9	122	0.1	82	46	<1	10	18	1.1	3.7	3.7	14
BC-5S	5.4	24	3.4	22	7	0.8	<2	1	0.7	0.8	1.9	11.5
BC-5i	5.5	18	5.8	26	7	<1	<2	0.8	0.6	0.6	2	12
BC-5D	6.2	50	3.5	44	22	<1	2.6	4.8	1.4	2	3	16
BC-6D	6.7	46	6.9	38	15	<1	<3.5	3.1	1	1.1	2.8	20
BC-7S	5.4	18	6.4	16	4	1	<2	0.7	0.7	1.2	1	6.9
BC-7i	5.6	12	7.5	14	3	1.1	<2	0.5	0.7	0.6	0.7	7
BC-7D	7.9	160	0.3	100	56	<1	15	23	3.3	4.3	8.7	10
Boyd Branch at BC2	6.8	18	8.6	25	7	<1	<2	1.2	0.7	0.8	1.6	12
trib to Boyd Branch at BC3	6.8	17	9.4	26		<5	<2	1.1	0.6	0.7	1.1	9.4
trib to Boyd Branch at BC7	6.9	22	7.8	28	6	<1	<2	1.6	0.9	0.7	1.8	13
Bent Creek	6.6	15	8.7	23	5	<1	<2	0.9	0.6	0.6	1.4	8
Arbor-3 (~ 2 mi from BCRS)	6.7	73		70	18	<1	12	0.6	2	2.1	4.7	
Arbor-4 (~ 2 mi from BCRS)	6.7	89		82	32	1.8	9.1	1.1	2.2	1.1	6.5	
Regional data												
NCDHHS, 2008[b] (n = 56 to 532)	7				47	<5	7	11.2	2.5		6	
Trapp, 1970[c] (4 counties, n = 62)	6.8	129			54	2.2	5.4	11	3	2.2	5.3	23
Briel, 1997[d] (Blue Ridge Province, n = 322 to 558)	6.6	103	6.2	73	32	2.1	5	8.3	2.5	1.2	5	16

[a] Saprolite well BC-2S was not included in statistical analyses due to potential grout contamination; [b] Data obtained from bedrock wells in Buncombe Co (n = 14 to 532, depending on constituent); [c] Data obtained from drilled bedrock drinking wells in Buncombe, Henderson, Transylvania, and Madison Counties (n = 62); [d] Data obtained from bedrock drinking wells in the Blue Ridge Province (n = 322 to 558, depending on constituent). Abbreviations: SC, specific conductance; DO, dissolved oxygen; Alk, alkalinity; TDS, total dissolved solids; HCO_3, bicarbonate; Cl, chloride; SO_4, sulfate; Ca, calcium; mg, magnesium; K, potassium; Na, sodium; Si, silica; mg/L, milligrams per liter; BB, Boyd Branch; BB trib, un-named tributary to Boyd Branch; BCRS, Bent Creek Research Station.

Table 16. Whole-rock chemistry oxide analyses for rock samples obtained from core holes BC-1, BC-3, and BC-7, Bent Creek Research Station, North Carolina

Rock samples from BCRS	Sample depth* ft bls	SiO2 %	Al2O3 %	Fe2O3 %	MgO %	CaO %	Na2O %	K2O %	TiO2 %	P2O5 %	MnO %
Core Hole at BC-1	31	54.1	22.8	9.5	2.7	0.5	0.6	4.0	1.1	0.2	0.2
Core Hole at BC-1	60	47.8	24.9	10.4	3.4	0.9	0.9	5.1	1.3	0.2	0.3
Core Hole at BC-1	124	52.7	22.1	10.8	2.9	1.7	1.8	3.1	1.0	0.3	0.2
Core Hole at BC-1	127	49.5	23.7	11.0	3.2	1.0	0.8	4.3	1.4	0.2	0.2
Core Hole at BC-3	60	67.8	14.0	6.6	2.1	1.4	2.6	2.6	1.0	0.2	0.1
Core Hole at BC-3	109	70.5	12.6	5.7	2.0	1.5	1.8	3.1	1.1	0.2	0.1
Core Hole at BC-3	125	48.7	13.4	6.1	5.9	11.6	2.0	2.8	0.4	0.5	0.2
Core Hole at BC-7	47	48.5	25.5	11.5	3.3	0.6	1.4	3.6	1.2	0.2	0.3
Core Hole at BC-7	104	43.3	27.0	13.1	4.0	1.6	1.5	3.8	1.5	0.3	0.2
Core Hole at BC-7	143	62.5	15.3	7.3	2.5	1.6	2.2	4.6	1.2	0.3	0.1
Rock samples from Bent Creek watershed (Merschat and Carter, 2002)											
Chl-mus schist		47.2	24.9	11.9	0.5	0.1	0.6	4.5	1.6	0.1	0.0
Chl-gar-mus schist		36.5	27.6	17.7	5.1	1.0	0.7	4.4	1.6	0.1	0.5
Chl-gar-mus schist		47.8	26.1	10.7	3.1	0.5	1.0	4.1	1.2	0.3	0.2
Gar-mica schist		45.4	25.8	12.4	2.5	0.1	0.7	5.1	1.1	0.1	0.2
Metagraywacke/bg		73.9	11.8	4.5	1.3	3.4	2.8	1.6	0.7	0.2	0.2
Metagraywacke/bg		66.6	13.9	6.0	1.8	1.5	2.8	3.6	1.0	0.1	0.1
Mig with metagraywacke/bg		67.0	17.2	3.5	1.1	2.6	5.4	2.6	0.6	0.0	0.0

Ft bls, feet below land surface; chl, chlorite; mus, muscovite; gar, garnet; mig, migmatite; bg, biotite gneiss

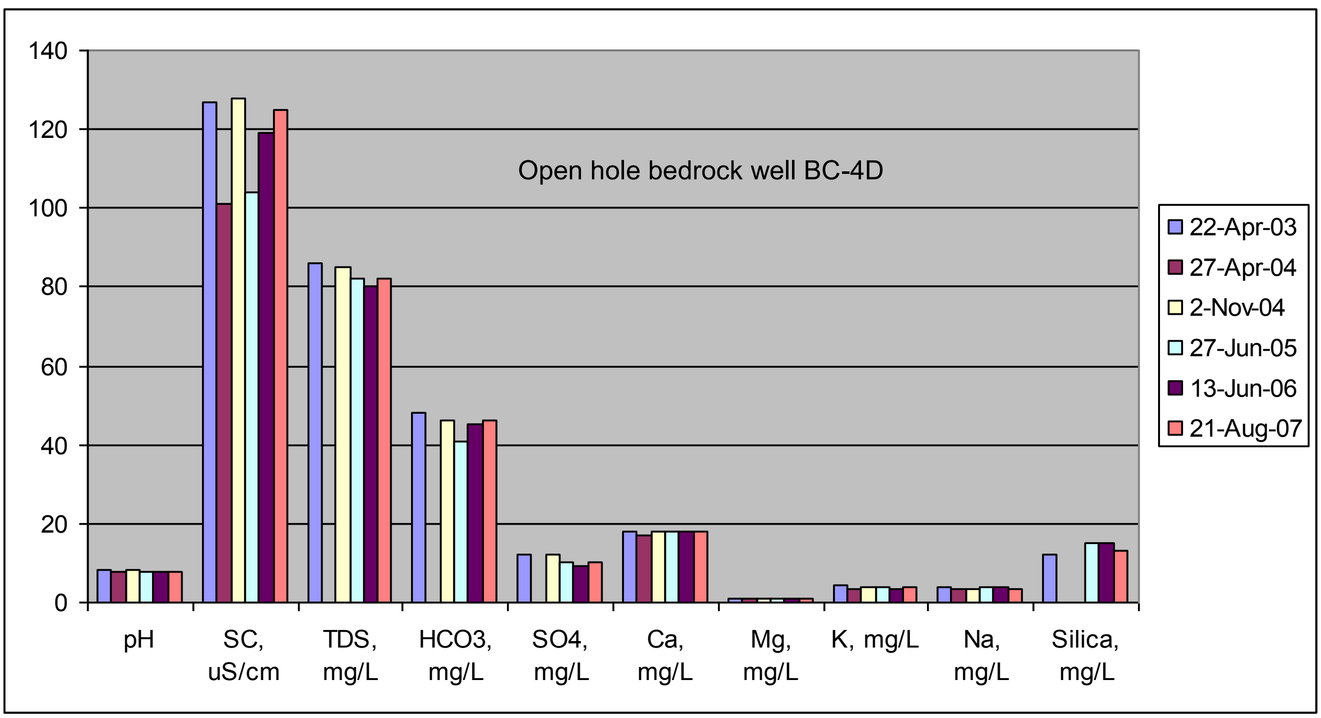

Figure. 47. Water quality results for selected parameters measured in open-hole bedrock well BC-4D at various sample dates from 2003 to 2007, Bent Creek Research Station, North Carolina.

Streams and upper regolith wells generally are characterized as a sodium/magnesium-bicarbonate type (figs. 45 and 46) and contain low SC (median = 18 and 17 uS/cm, respectively), low dissolved solids (median = 26 and 19 mg/L, respectively), and relatively high DO (median= 8.7 and 6 mg/L, respectively) (tables 14 and15 and fig. 48). Streams had a near neutral pH (median = 6.8), and the upper regolith and lower regolith wells were slightly acidic (median = 5.4 and 5.5, respectively). Trends were not noted in groundwater chemistry from recharge to discharge areas in the upper regolith flow system.

Water from six lower regolith wells was similar to that of upper regolith wells, suggesting generally well-mixed or very similar geologic conditions within the regolith flow system. The lower regolith wells, like those of the upper regolith, generally are characterized as a sodium/magnesium-bicarbonate type (figs. 45 and 46), and are associated with low SC (median = 16 uS/cm), low dissolved solids (median = 22 mg/L), and relatively high DO (median = 7 mg/L) (fig. 47) (tables 14 and 15 and fig. 48). Trends were not noted in groundwater chemistry from recharge to discharge areas in the lower regolith (transition zone) flow system.

Water from seven open-hole bedrock wells generally is characterized as a calcium-bicarbonate type , with the exception of BC-2D, which is a calcium/sodium-bicarbonate type (figs. 45 and 46). Groundwater residence times are longer for bedrock wells than for regolith wells, and, in general, the longer the water is in contact with soil and rock, the greater the mineral dissolution. As a result, bedrock wells contained significantly higher dissolved ions than regolith wells. The pH and SC in bedrock wells are significantly higher (median = 7.9 and 122 uS/cm, respectively) and the DO significantly lower (median = 0.2 mg/L), than the values observed in the regolith wells (tables 14 and 15 and fig. 48). Major ions, including calcium, magnesium, sodium, bicarbonate, chloride, and sulfate, are significantly higher in bedrock wells than in regolith wells (figs. 49 and 50). Total dissolved solids generally were about 1.3 times the SC in regolith wells and about 0.7 times the SC in bedrock wells. Trends were not noted in groundwater chemistry from recharge to discharge areas in the fractured bedrock flow system.

Relatively high levels of pH, calcium, bicarbonate, and sulfate and low DO were observed in 4 of the 7 bedrock wells located in both discharge (BC-2D) and recharge (BC-3D, -4D, and -7D) areas (table 15). Likely, these results are due to a combination of factors including (1) the lithologic composition and degree of weathering of host rock through which the sampled groundwater flowed, (2) the length of time the water spent in contact with the host rock, and (3) potential grout contamination during drilling and well completion activities. Calcium-rich feldspars such as plagioclase are found in varying concentrations throughout the study area rocks, particularly the metagraywackes (plagioclase content from 32 to 42 percent) and the less commonly occurring amphibolites (plagioclase content from trace to 38 percent) (Merschat and Carter, 2002, appendix 1a). Moreover, calcium-rich amphibole outcroppings are present in the general vicinity or upgradient of these four areas (Merschat and Carter, 2002). Another source of calcium common in the study area is the silicate accessory mineral garnet. Rock samples analyzed for calcium oxide (CaO) varied from 1.4 to 11.6 percent at 3 depths in core hole BC-3, and 0.6 to 1.6 percent at the 3 depths in core hole BC-7 (table 16). The finding of 11.6 percent calcium oxide at one depth in corehole BC-3 may be associated with an interlayered sequence of calcium-bearing amphibole, which occurs locally in some parts of the Bent Creek study area, or a dominant layer of migmatite.

Silica concentrations ranged from 6.9 to 23 mg/L and generally were higher in bedrock wells (associated with longer residence times) than in regolith wells (fig. 51). A principal source of dissolved silica is the weathering and decomposition of mineral silicates present in the parent rock, leaving behind clay minerals in the weathered portions of rock.

(A) pH

(B) Specific Conductance

(C) Dissolved Oxygen

n upper regolith = 5

n lower regolith = 6

n bedrock = 7

n streams = 4

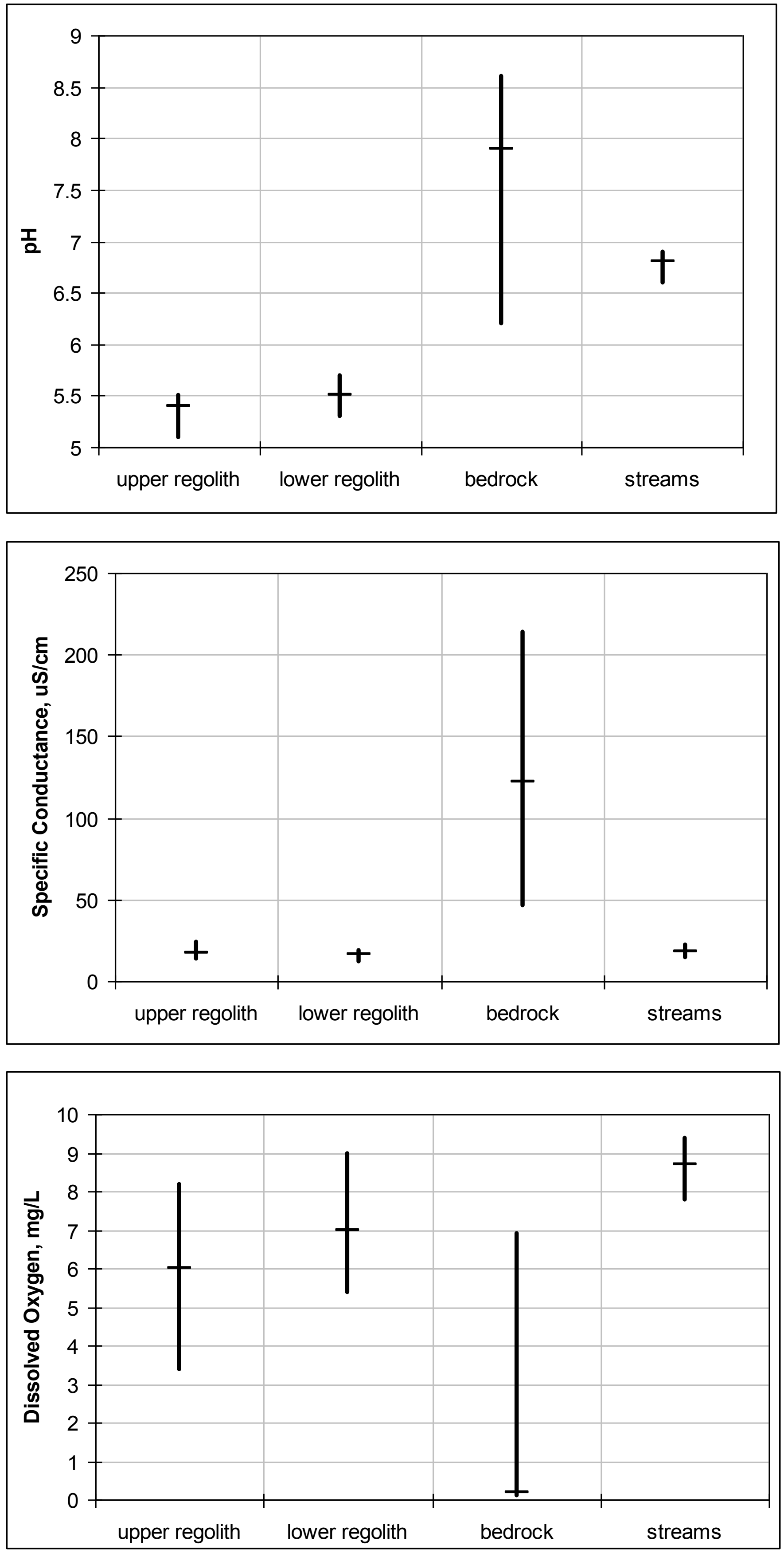

Figure 48. Range and median values for (A) pH, (B) specific conductance, and (C) dissolved oxygen in wells and streams during periodic sampling events between 2003 and 2007, Bent Creek Research Station, North Carolina.

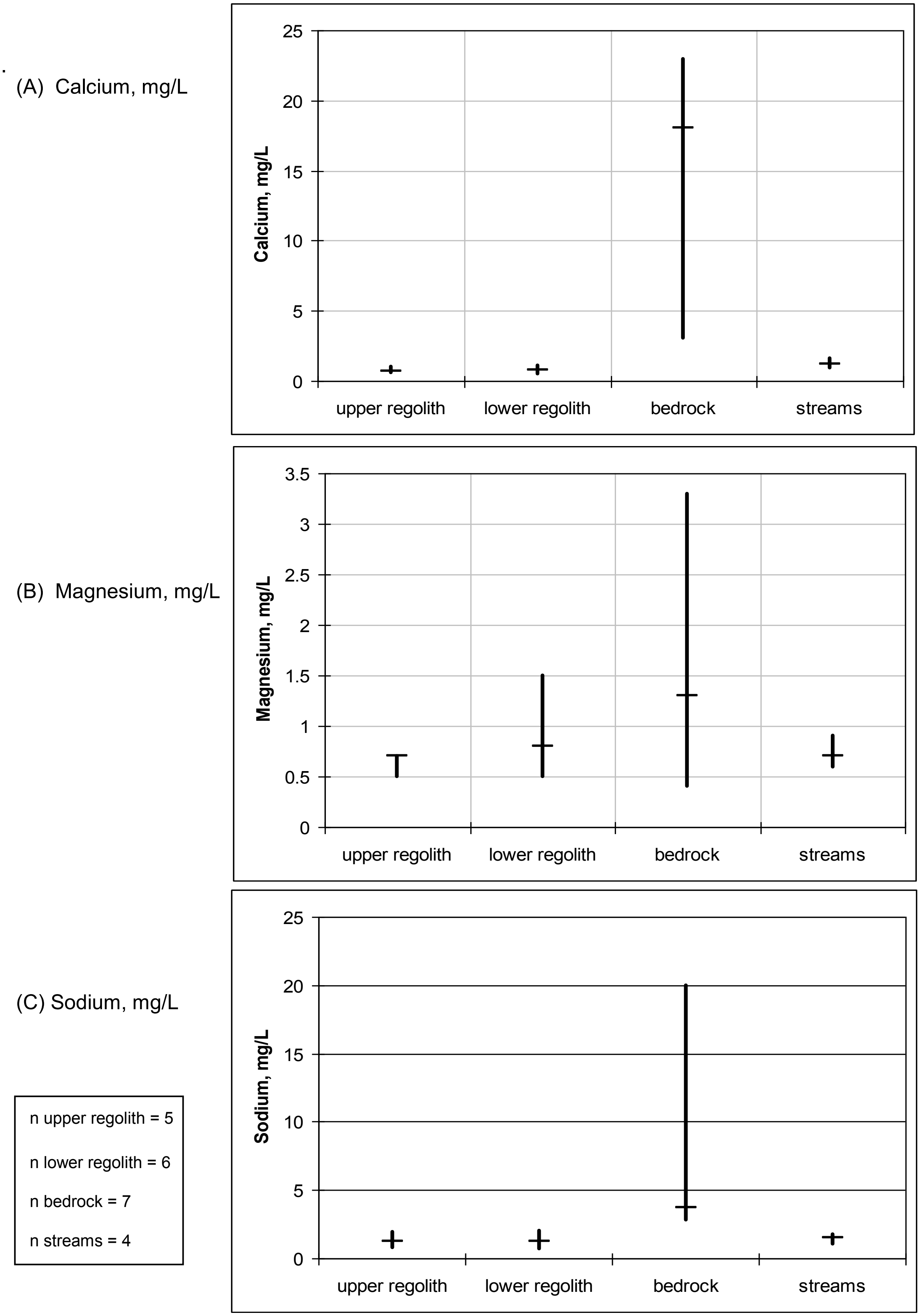

Figure 49. Range and median values for (A) calcium, (B) magnesium, and (C) sodium in wells and streams during periodic sampling events between 2003 and 2007, Bent Creek Research Station, North Carolina.

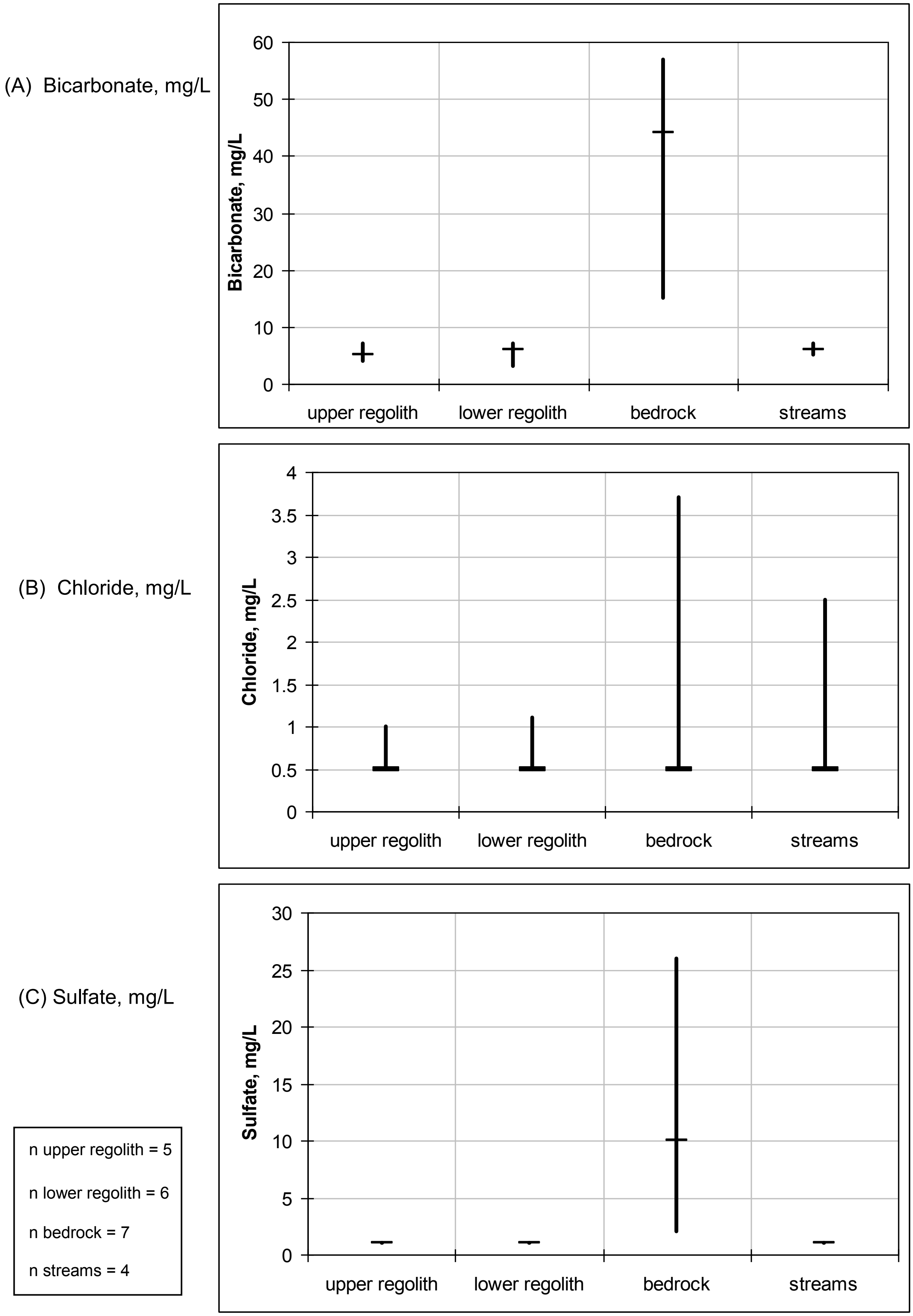

Figure 50. Range and median values for (A) bicarbonate, (B) chloride, and (C) sulfate in wells and streams during periodic sampling events between 2003 and 2007, Bent Creek Research Station, North Carolina.

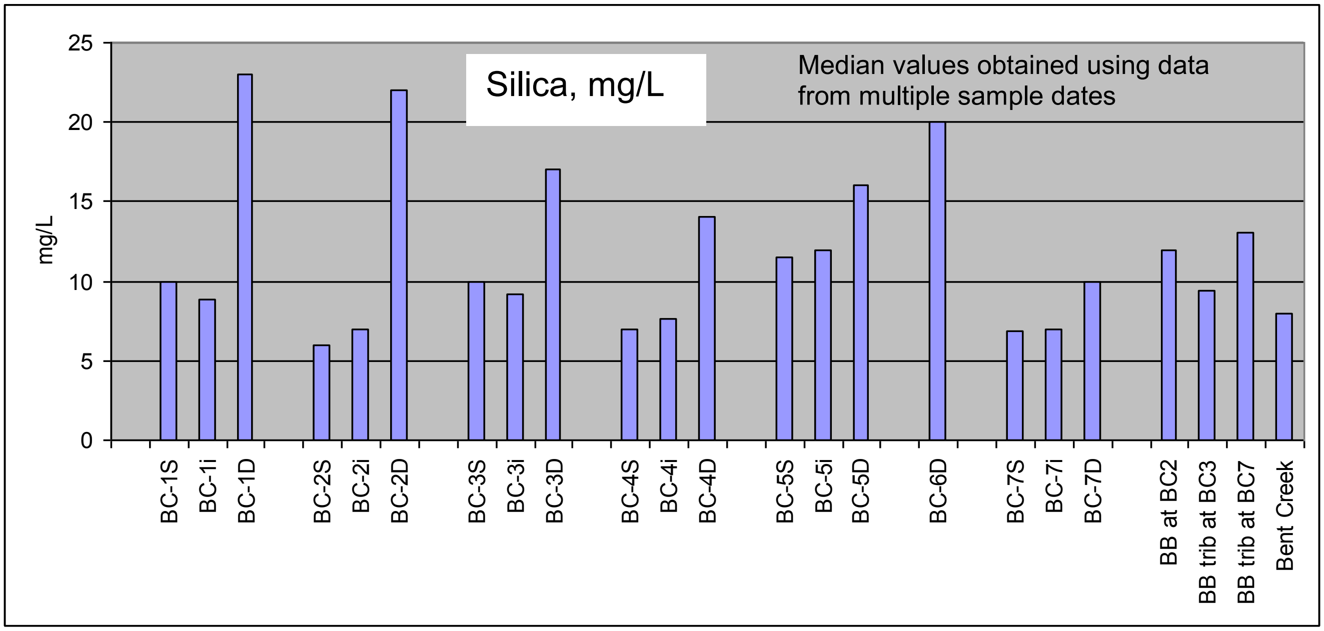

Figure. 51. Median silica concentrations observed in stream and well samples during periodic sampling events between 2003 and 2007, Bent Creek Research Station, North Carolina.

Changes in Groundwater Quality with Short-Term Rainfall Events

Storm-induced upwelling of water from the bedrock system to the regolith system was documented at well cluster BC-2 (discharge area with artesian conditions) using hourly water quality data. Hourly recordings of water level, SC, and DO in lower regolith well BC-2I from February 2005 to March 2005 were logged and plotted (fig. 52A). As storm-induced water levels increased rapidly, SC temporarily increased, and DO temporarily decreased in lower regolith well BC-2I. Water in the bedrock system at BC-2 contains significantly higher SC and significantly lower DO than water in the regolith system (median SC in bedrock well BC-2D is 214 uS/cm and in BC-2I is 19 uS/cm; DO in bedrock well BC-2D is 0.1 mg/L and in BC-2I is 6 mg/L). As shown in fig. 52, one inch of rain occurred in a 24-hour period between February 20 and 21, 2005, and within hours resulted in a distinct and near simultaneous increase in SC (from 10 to 38 uS/cm) and water levels (fig. 52A) and a decrease in DO (from 8 to 5 mg/L)(fig. 52B). All but about 30 percent of the rise/fall in levels dissipated over the next 7 days, consistent with patterns observed during other rainfall events during the 14-month measurement period. Site 2 is in a discharge area with a strong upward vertical head gradient from the deeper bedrock system to the regolith system (fig. 25F). Rainfall recharge to the upper regolith may not penetrate downward into the lower regolith system in this location, and may instead move laterally and discharge to Boyd Branch. Vertical head gradients within the regolith itself (between the upper regolith and lower regolith) are mostly neutral, and temperature in lower regolith well BC-2I remained stable during individual rainfall events (figs. 35A, 36A) while temperature in upper regolith well BC-2S fluctuated (figs. 35A and 36A). This is consistent with conditions in a discharge area and has been documented at a NCDWQ-USGS Piedmont groundwater research station near Raleigh, North Carolina (Chapman and others, 2005).

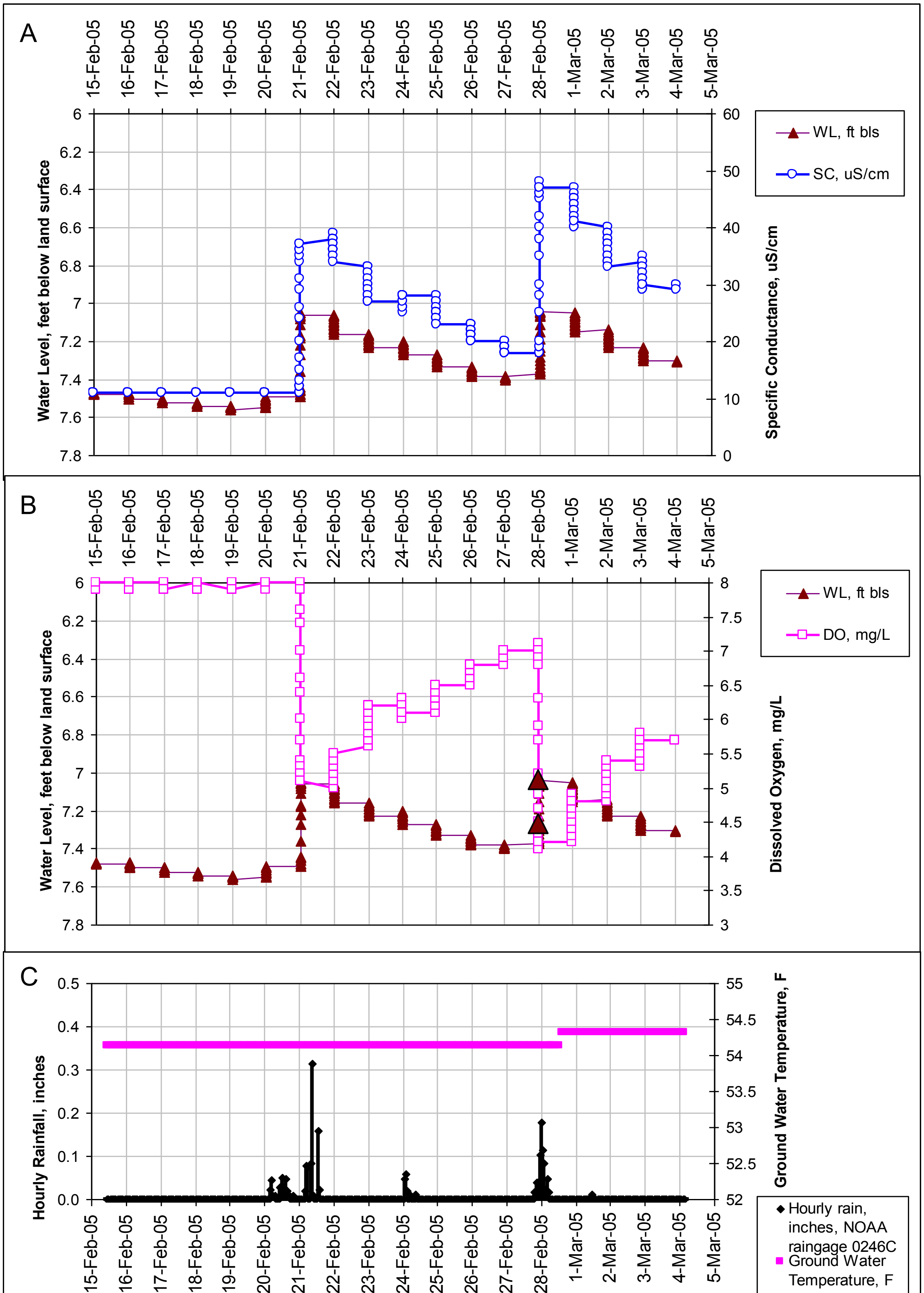

Figure. 52. Hourly recordings in lower regolith well BC-2I for (A) specific conductance, (B) dissolved oxygen and water levels, and (C) ground-water temperature, in response to storm events from February 15 to March 5, 2005, Bent Creek Research Station, North Carolina.

Nutrients and Bacteria

Several nutrients were analyzed at study area wells and stream locations, including TKN, nitrate plus nitrite as nitrogen (N), ammonia as N, nitrate as N, nitrite as N, total phosphorous as P, and phosphate. Nutrient concentrations were very low or not detected (below 0.4 mg/L) in all wells and stream samples, with the exception of a nitrate value of 2.7 mg/L at BC-4S during one sample event in 2003 (all four other sample events at BC-4S showed nitrate levels below the detection limit). Most samples were below the detection limit for all nutrients analyzed. Detections were somewhat more common in stream samples than well samples, and detections were slightly more common in regolith wells than in bedrock wells. Locations that are vulnerable to surface runoff of fertilizers and animal wastes (such as streams and shallow wells) are more likely to have nutrient detections than properly constructed bedrock wells. No samples exceeded state or federal nutrient standards.

Fecal and total coliform values generally were near or below 1 colony per mL for all wells. Positive detections of total and fecal coliform occurred in all sampled surface waters, with a total coliform range of 130 to 900 colonies per mL and a fecal coliform range of 34 to 76 colonies per mL. The highest observations occurred in the tributary to Boyd Branch, adjacent to BC-7.

Volatile Organics, Semi-Volatile Organics, Pesticides, Herbicides, and Other Constituents and Measures

As expected in the pristine setting of the study area, pesticides, herbicides, semivolatile organics, and volatile organic compounds essentially were absent from all sampled wells and streams in this pristine study area. Minor exceptions were attributed to artifacts of the sampling and analytical process.

Total organic carbon was below the detection limit of between 2 and 5 mg/L for all well and stream samples. Similarly, biological oxygen demand and chemical oxygen demand were below their respective detection limits of 2 mg/L and 20 mg/L for all well and stream samples. Total suspended solids (TSS) values were generally at or near the detection limit of between 2.5 and 6.2 mg/L. An exception was at BC-7S where the TSS concentration was about 30 mg/L.

Naturally Occurring Radionuclides and Arsenic

The primary naturally occurring compounds measured during the study included total uranium, radium-226, radon-222 (radon), and arsenic. Gross beta activity also was measured and occurs both naturally and as a man-made product from the nuclear industry. Total uranium levels were very low or were below the detection limit of 0.02 µg/L, with 22 of 23 locations below 1.6 µg/L. The exception was a value of 5 µg/L at BC-4D. The EPA MCL for uranium is 30 µg/L. Radium-226 values also were very low with 22 of 23 locations below 0.09 picocuries per liter (pCi/L) and one location (BC-1D) at 0.38 pCi/L. The EPA MCL for combined radium-226 + radium-228 is 5 pCi/L.

Dissolved radon was detected above 100 pCi/L at 16 of 17 wells and ranged from 90 to 5310 pCi/L (median for all wells = 1300 pCi/L) (fig. 53). Average radon values were higher at well cluster BC-1 (average = 4040 pCi/L) and well cluster BC-5 (average = 2250 pCi/L) than well clusters BC-2, -3, -4, and -7, which averaged 1520, 1150, 1400, and 550 pCi/L, respectively. Concentrations in regolith wells were not significantly different than concentration in bedrock wells. Because radon volatilizes rapidly, it was not measured in streams. The EPA has proposed an MCL of 300 pCi/L for radon in water and an alternate standard of 4000 pCi/L for water suppliers with a radon mitigation and outreach program (U.S. EPA, 2003), but, to date, neither standard has been promulgated. Radon is a natural decay product of uranium-238 (its immediate parent is radium-226) and is common in uranium rich granitic rocks and, to a lesser degree, in other rocks in the Piedmont-Mountains of North Carolina, including schists like those in the study area. The lifetime health risk associated with ingesting radon in water at the median value of 1300 pCi/L is about 1 in 13,000 (NRC, 1999). Arsenic was below the detection limit of between 5 and 10 µg/L at all sampled wells and streams.

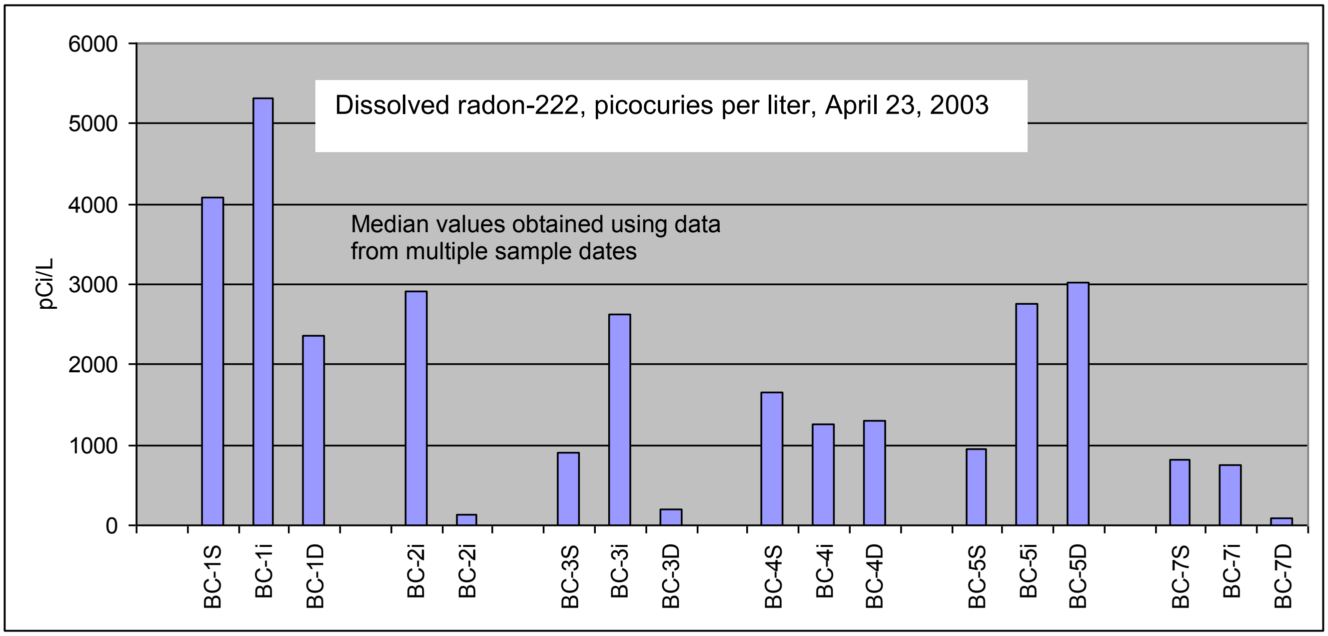

Figure. 53. Median dissolved radon-222 concentrations observed in well samples during periodic sampling events between 2003 and 2007, Bent Creek Research Station, North Carolina.

Comparison of Groundwater Chemistry to Rock Chemistry

Whole-rock analyses from core samples (three depths at each of three locations, BC-1, BC-3, and BC-7) were compared to groundwater chemistry from the seven bedrock wells (table 16). Rock core recovered from these locations consisted of interlayered schist, biotite gneiss/metagraywacke, and migmatite. Using the average oxide percentage from these samples (all depths and locations), the dominant whole rock ion species were silica (51%), aluminum (20%), iron (9%), potassium (3.6%), magnesium (3.2%), calcium (2.4%), and sodium (1.4%). One sample (BC-3, at a depth of 125 ft) had a relatively high calcium oxide content of 11.6%. From the samples analyzed by Merschat and Carter (2002) across the Bent Creek watershed, the dominant whole rock ion species for schist, metagraywacke, and migmatite samples were silica (44%, 70%, and 67%, respectively), aluminum (26%, 13%, and 17%, respectively), iron (13.2%, 5.3%, and 3.5%, respectively), potassium (4.5%, 2.6%, and 2.6%, respectively), magnesium (2.8%, 1.6%, and 1.1%, respectively), sodium (0.8%, 2.8%, and 5.4%, respectively), and calcium (0.4%, 2.5%, and 2.6%, respectively). In comparison, median ion values from all bedrock well groundwater results were calcium (18 mg/L), silica (17 mg/L), sodium (3.7 mg/L), potassium (2 mg/L), magnesium (1.3 mg/L), iron (0.2 mg/L), and aluminum (<0.05 mg/L).

SUMMARY

The BCRS is one of ten hydrogeologic research stations in the Piedmont-Mountains installed to evaluate groundwater availability, flow, and quality as part of the cooperative NCDENR-USGS REP. The BCRS represents a well-foliated mica schist geologic type area, with lesser amounts of interlayered, poorly foliated biotite gneiss and migmatite.

Groundwater in the study area occurs within a three-part flow system: upper regolith, lower regolith, and fractured bedrock. The upper regolith system has a high porosity and variable permeability and consisted of sandy, clayey, silty residuum-saprolite. The lower regolith system has a variable porosity and high permeability and consisted of partially weathered transition zone material with both primary porosity (pore spaces) and secondary porosity (rock partings and veins). The thickness of the regolith system measured in the study area ranged from 33 to 60 feet (median = 48 ft). The upper regolith ranged from 2 to 38 feet thick (median = 23 ft), and the lower regolith ranged from 5 to 46 feet thick (median = 19 ft). Because of differential weathering, the thickness, composition, and permeability of the upper and lower flow systems varied with location, as did the depth to bedrock, and interlayering of saprolite, transition zone material, and un-weathered bedrock occurred in 3 of 7 core holes. This finding has implications for the proper design and construction of contamination assessment and water supply wells at similar settings within the Piedmont and Mountain regions.

Depth to competent bedrock ranged from 33 to 60 feet below land surface. Bedrock foliations strike predominantly to the NE and dip to the NW and SE at angles of 25 to 85 degrees. Bedrock fractures generally cross cut foliation and strike predominantly NW, dipping to the NE or SW at angles of 50 to 70 degrees. Less often, fractures are parallel to foliation or are of a stress relief type.

Lower regolith (transition zone) wells transmitted water much more readily than did upper regolith (saprolite) wells, with a median yield and hydraulic conductivity of 5 gallons per minute and 8 feet per day, respectively, as compared to 1.5 gpm and 2 feet per day for saprolite wells.

Bedrock was characterized by low porosity and permeability. Bedrock well yields ranged from less than 0.5 to 40 gpm (median = 1 gpm and average = 7 gpm). These yields are far lower than the average yield of 16 to 22 gpm reported in similar hydrogeologic units elsewhere in the Piedmont-Mountains of North Carolina (Daniel, 1989). This may be due to the combined effect of lithology (predominantly schist, whose laminated cleavage planes can readily fold and deform without fracturing), structure (a relative lack of low angle water bearing fractures and foliations), and the fact that the wells were not drilled in locations or to depths that were intended to maximize yields. Rock coring, heat pulse flow metering, and optical televiewer imaging indicated relatively few primary (open and significant) fractures at seven well locations. Results from a 45-hour aquifer pumping test conducted in a bedrock well support this assessment and demonstrated a lack of connectivity between the pumped well and two bedrock wells located within 1500 feet. The response in overlying regolith wells within 250 feet generally was modest and sluggish, with total drawdowns of about a half foot or less.

Groundwater flow at BCRS generally is from topographic highs to lows, consistent with conceptual models of flow in the Blue Ridge and Piedmont physiographic provinces. Vertical head gradients generally are downward in upslope and midslope recharge areas and upward in downslope discharge areas. Storm events produced a rapid, temporary increase of about 0.5 to 3 feet in water levels in regolith and bedrock wells, which dissipated after 4 to 8 days. Water temperature and vertical head gradients in clustered wells were used to demonstrate upwelling from the deeper to the shallower groundwater system during rain events in a low-lying discharge area. Data indicate that at least some recharge infiltrates to the water table within 0.5 to 2 days of rainfall events in two low-lying discharge areas. Age estimates of groundwater in four bedrock wells ranged from about 20 to 50 years, and, within a given well, a mixture of ages was common (including water less than 2 years old in at least one upslope bedrock well). Observing a mixture of older and younger waters within bedrock wells is consistent with the regional conceptual model in which multiple potential flow paths (and source waters) contribute to the total volume of water in a bedrock well.

Bent Creek, a 3rd order stream draining the larger watershed, is a major control on groundwater flow direction in the Boyd Branch sub-basin. Locally, groundwater also discharges to Boyd Branch, a small, weakly incised 2nd order tributary to Bent Creek. Groundwater under-flowed Boyd Branch in one measured reach. This is significant when considering issues of contaminant transport and groundwater flow direction in mountain watersheds, and demonstrates the importance of understanding several factors that may affect groundwater flow direction and potential underflow of mountain streams, including: depth to water, depth of stream incision, underlying geology and thickness of regolith, size and shape of recharge boundaries, and relative topographic differences in both the sub-basin and the larger watershed of which it is part.

The water table typically occurred at a depth of about 3 to 32 feet below land surface and varied seasonally and with topographic setting. Artesian flow conditions occur at one downslope location. Water levels tended to be lowest in late summer when evapotranspiration effects tend to be greater than recharge, and highest in late winter. Groundwater temperatures lagged seasonal air temperatures by 1 to 4 months in the upper regolith and by 3 to 7 months in the lower regolith. Temperatures in bedrock wells remained stable across seasons and storm events.

Annual mean streamflow in Bent Creek is estimated to be about 15 cfs (6700 gpm) based on hydrograph separation computations using stream flow records and the USGS PART program

(Rutledge, 1998). The program calculated baseflow in the pristine, largely undisturbed forest to be about 80 percent of this amount, or 12 cfs (5400 gpm). Hourly mean stream flow in Boyd Branch ranged from 0.5 (220 gpm) to 56 cfs (25,000 gpm) for the period between March 2004 and November 2005, with a median of 1.5 cfs (670 gpm) at USGS gage 0344789265 in Boyd Branch at Bent Creek Road near Lake Powhatan. Baseflow was not estimated due to the limited period of record.

The dominant water type for bedrock wells is calcium bicarbonate, and for streams and regolith wells is sodium/magnesium-bicarbonate. Ground and surface water are relatively soft, of high quality, and suitable for most domestic and industrial-use purposes. Values of pH, calcium, magnesium, and sulfate were higher than typical regional levels in some of the BCRS bedrock wells, due in part to the rock type and local geochemistry. Deeper groundwater contained higher amounts of dissolved ions than shallow groundwater due to increased residence time for the dissolution of minerals. Iron and manganese staining was common in the regolith at core locations (primarily within the transition zone), indicative of oxidation-reduction reactions in the weathered, aerobic portion of the aquifer. Staining occurred less frequently in the underlying bedrock fractures, particularly in anaerobic settings such as discharge areas. Fecal bacteria, nutrients, pesticides, herbicides, volatile and semi-volatile organic compounds, and naturally occurring arsenic generally were not detected. Naturally occurring uranium and radium-226 levels generally were near or below the detection limit, and radon-222 was found above the proposed EPA standard of 300 picocuries per liter in 3 deep wells, with a high of 3030 picocuries per liter.

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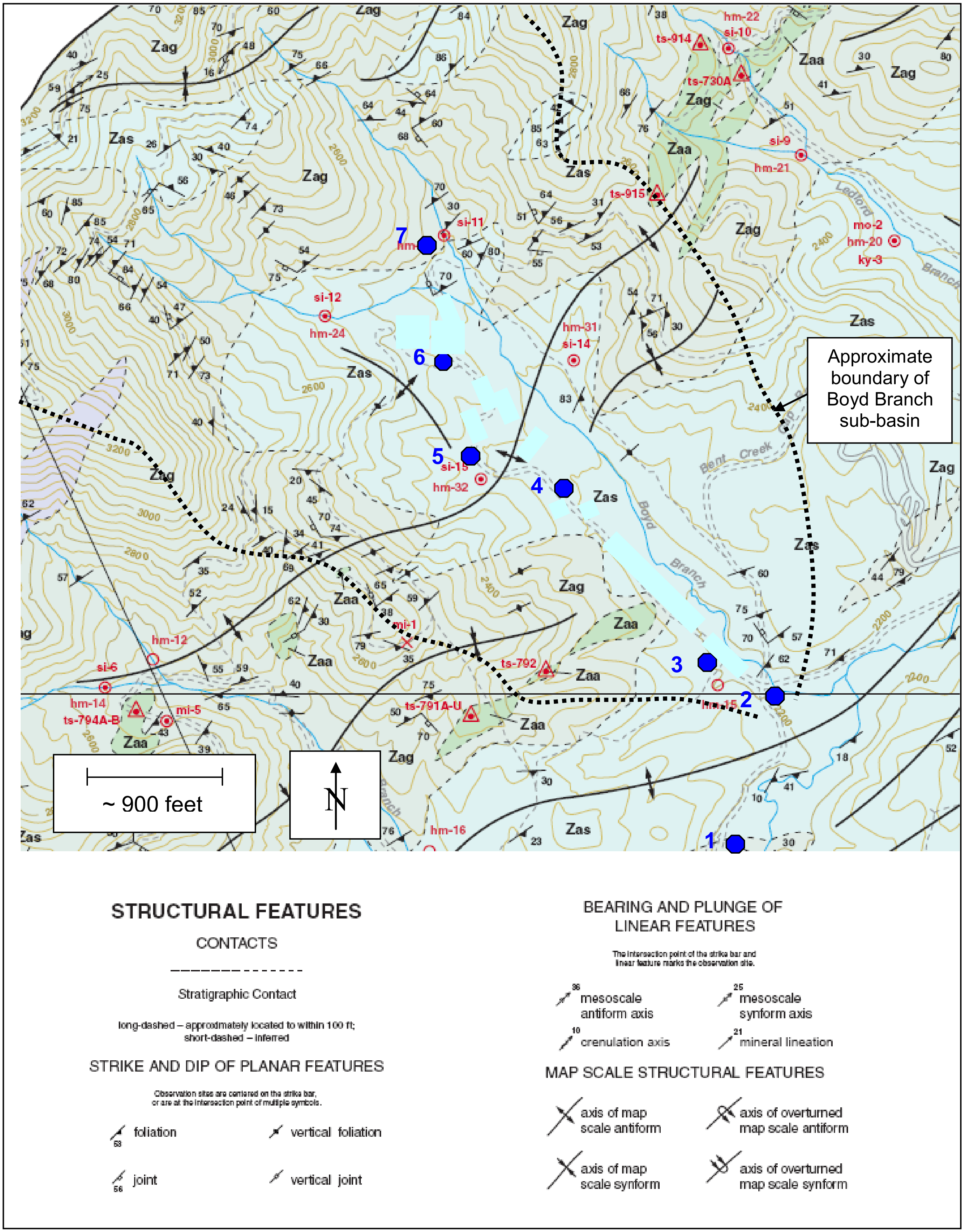
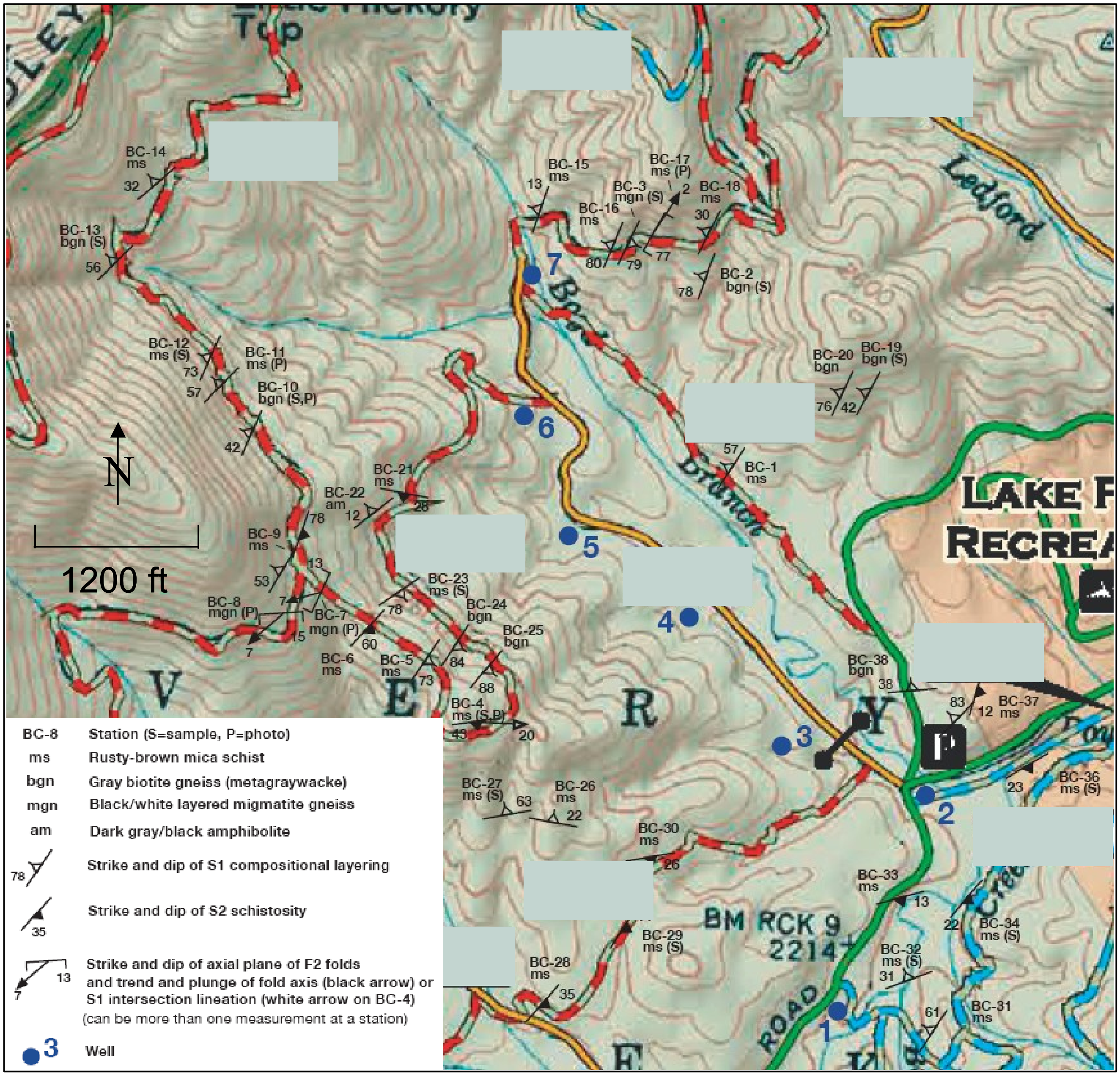
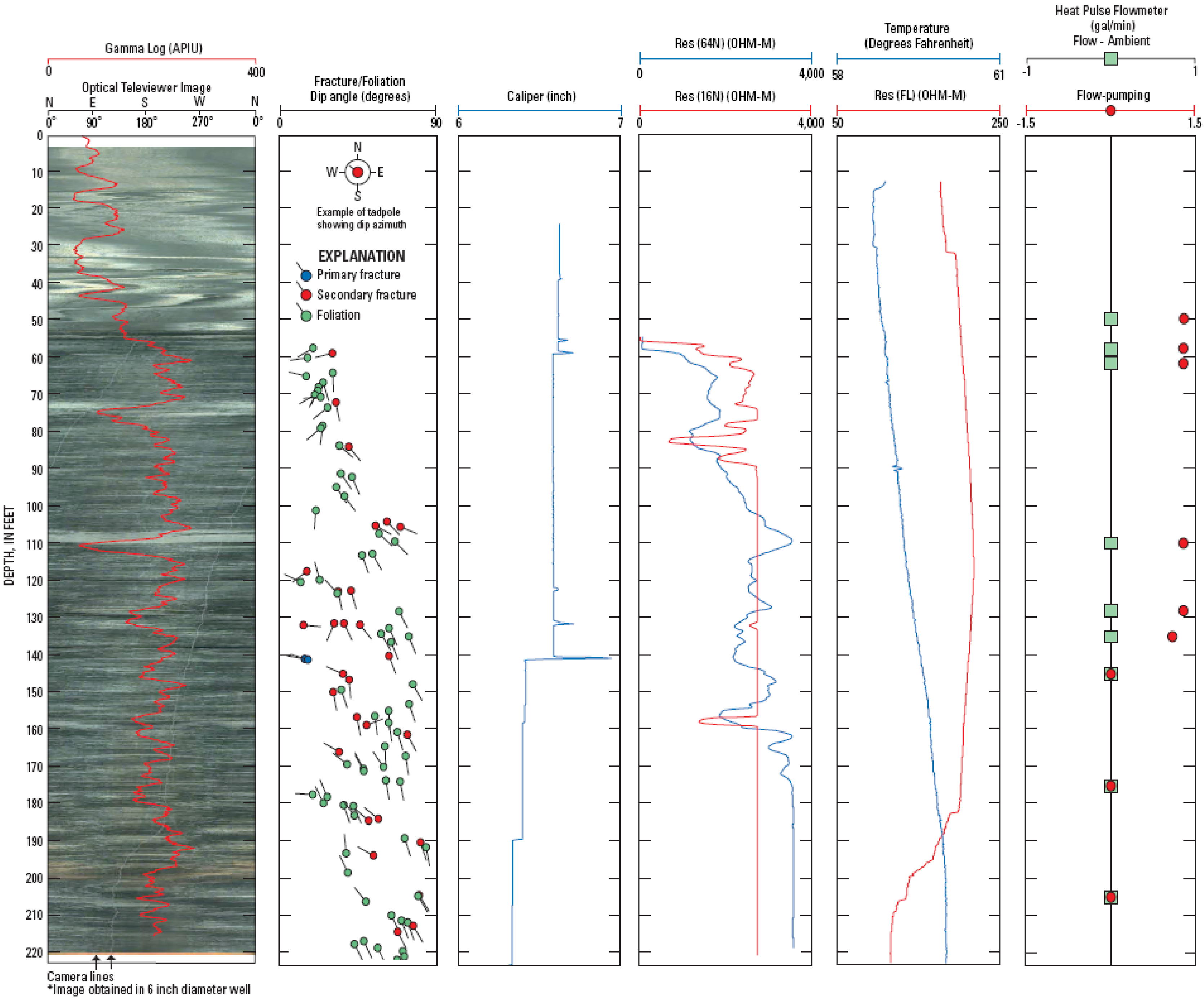
APPENDIX 1A. Geology and structural features in the vicinity of Boyd Branch, Bent Creek Experimental Forest watershed, North Carolina, as modified from 1:12,000 scale map by Merschat and Carter, 2002.



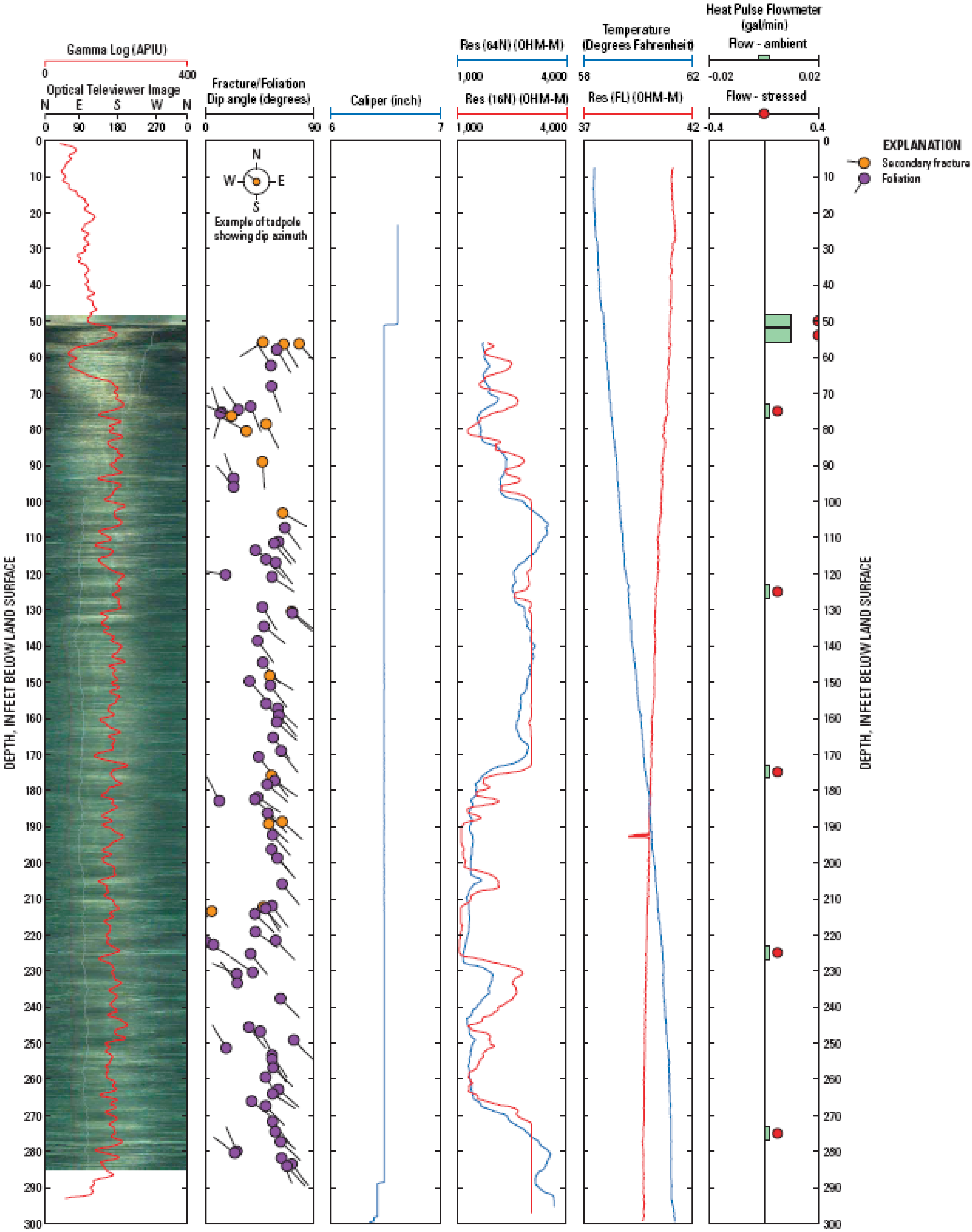
APPENDIX 1B. Geology and structural features in the vicinity of Boyd Branch, Bent Creek Experimental Forest watershed, North Carolina, written communication, B. Burton, July 25, 2008.



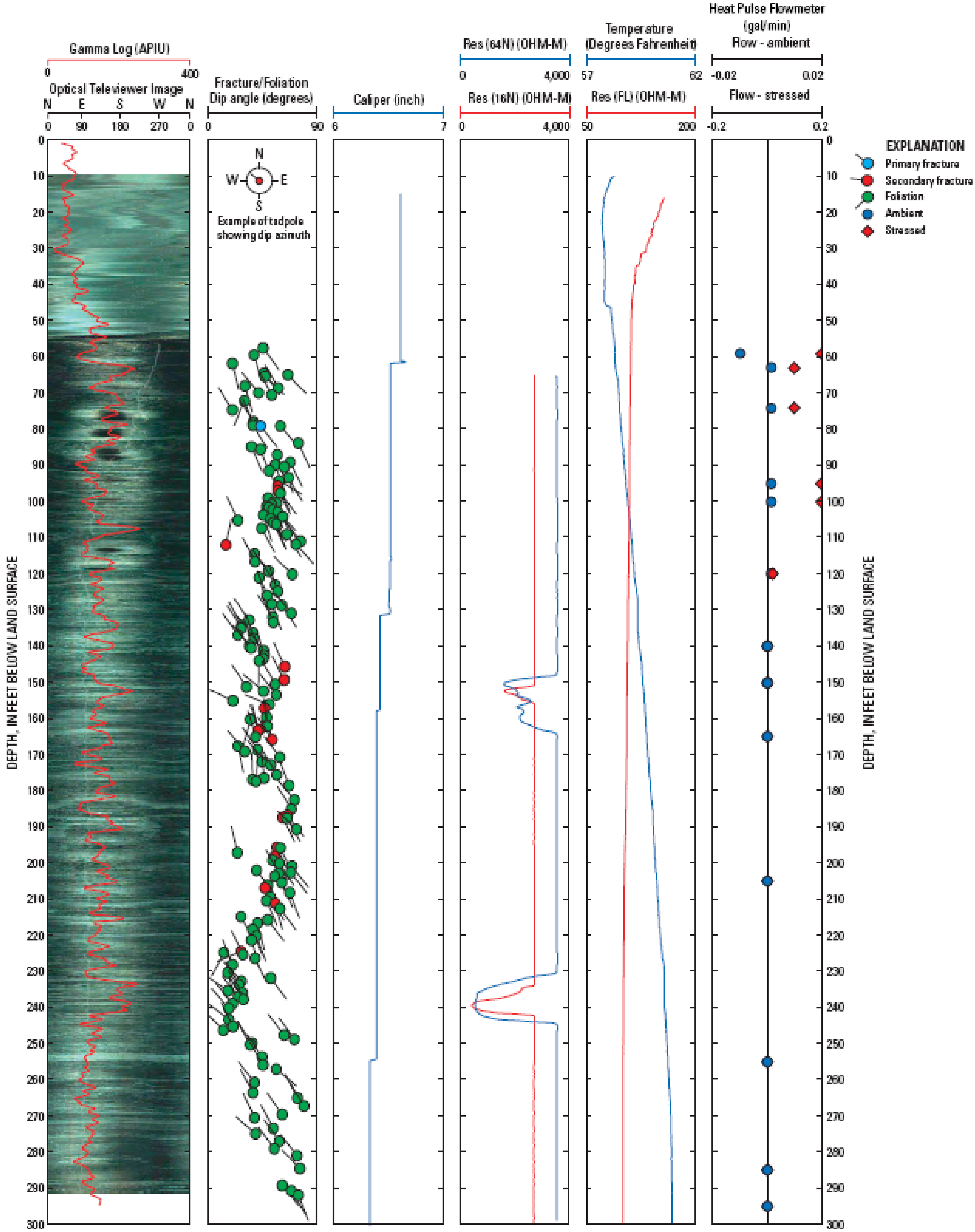
APPENDIX 2. Geophysical and optical televiewer logs for bedrock wells BC-1D at Bent Creek Research Station, North Carolina.



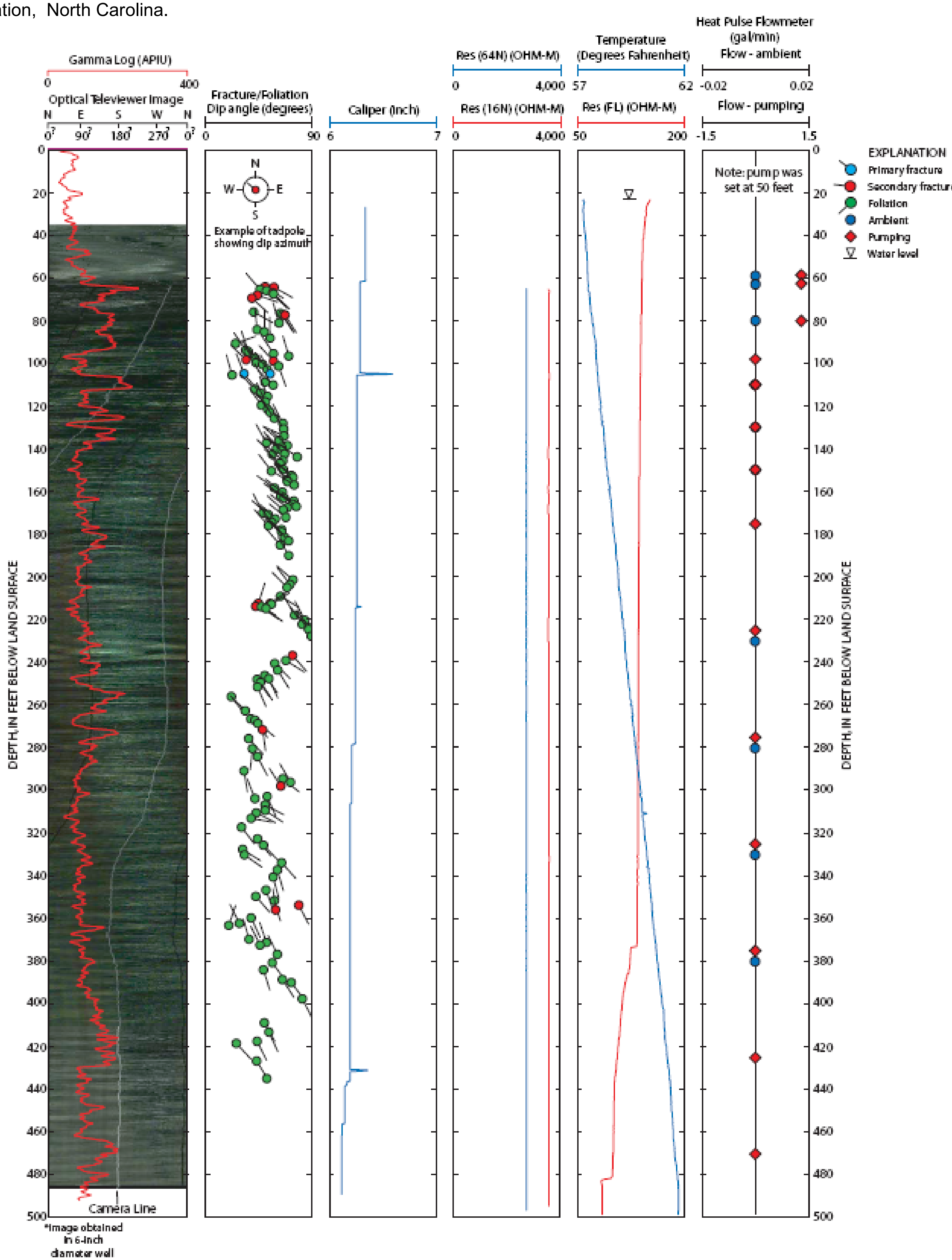
APPENDIX 2 Continued. Geophysical and optical televiewer logs for bedrock wells BC-2D at Bent Creek Research Station, North Carolina.



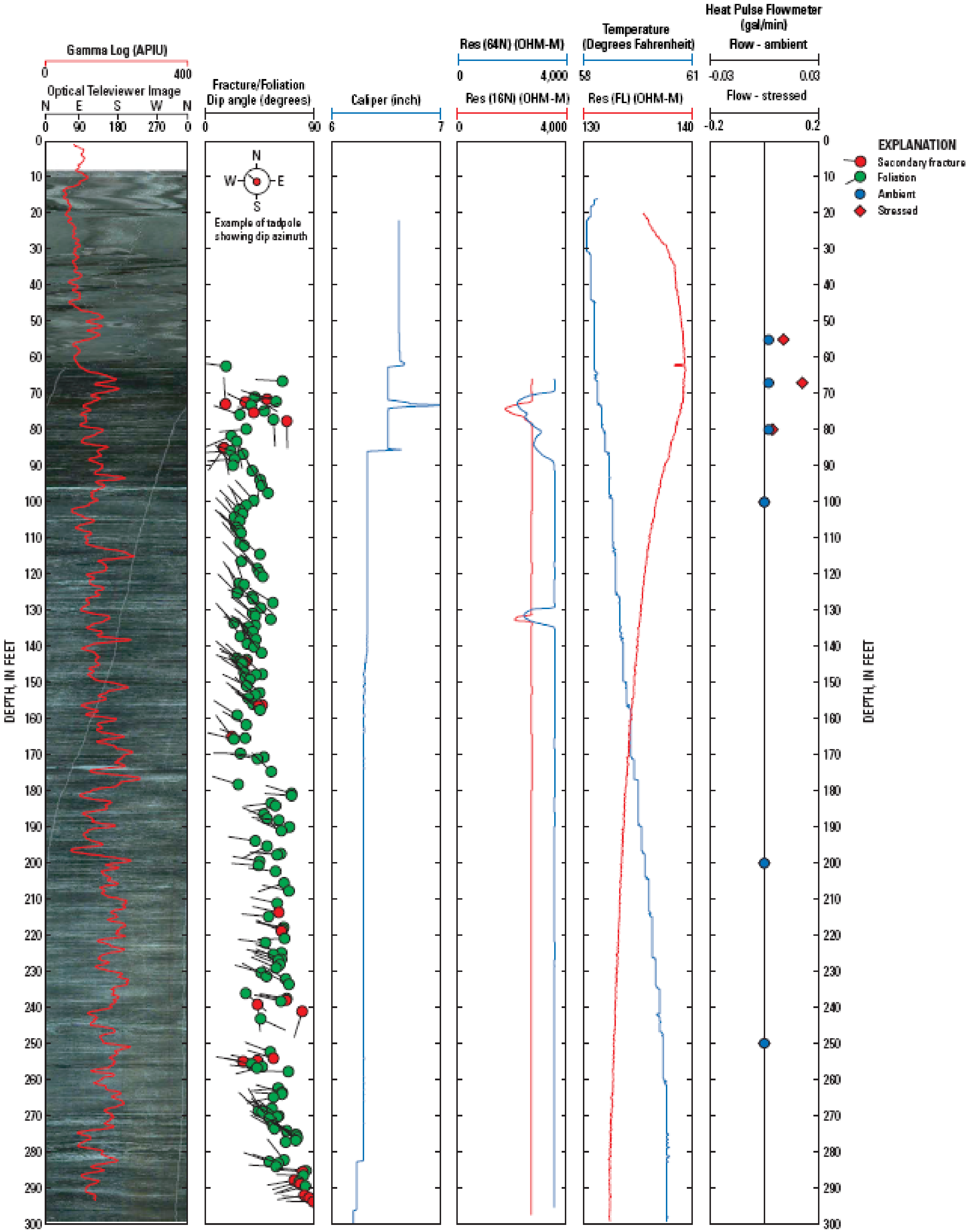
APPENDIX 2, continued. Geophysical and optical televiewer logs for bedrock wells BC-3D at Bent Creek Research Station, North Carolina.



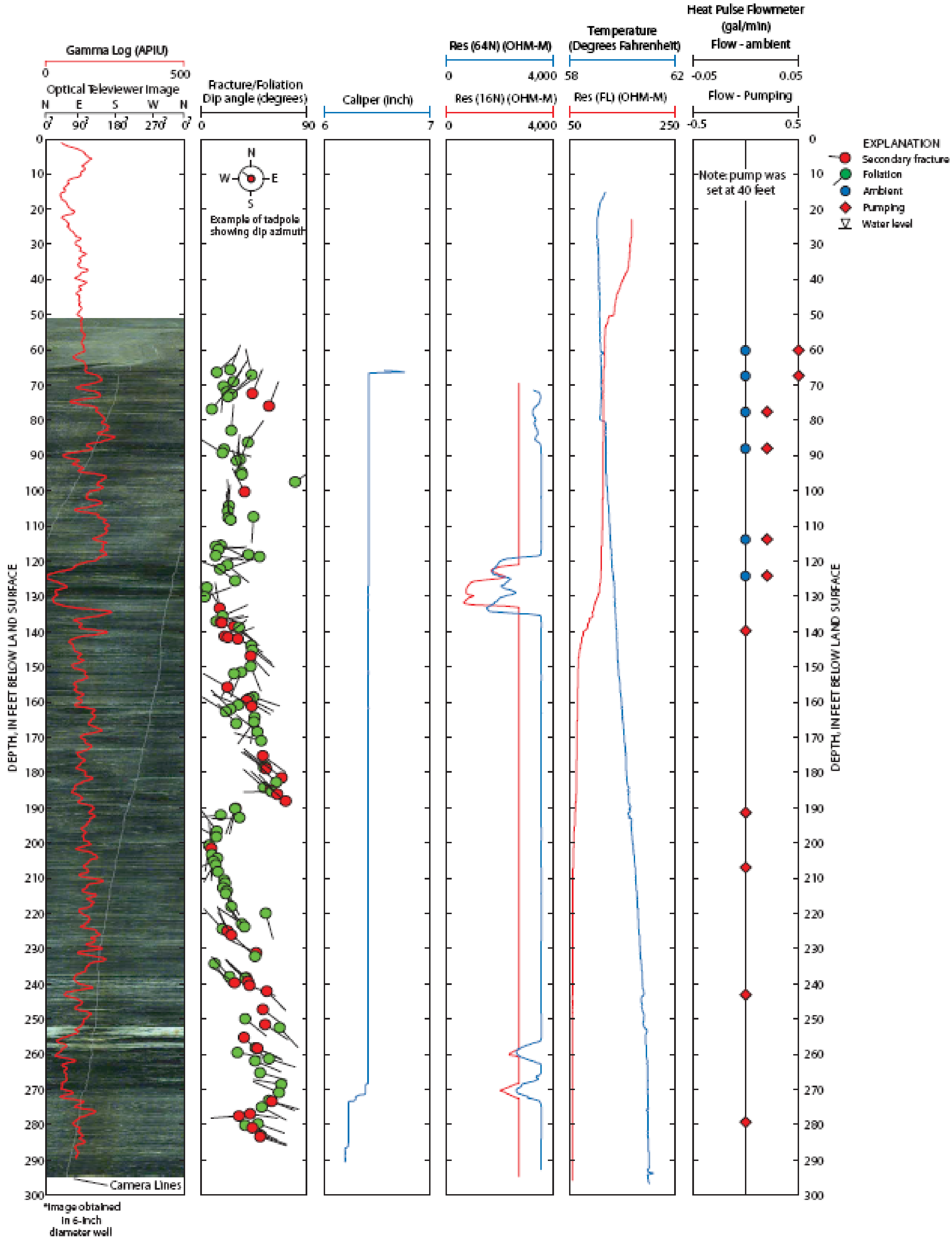
APPENDIX 2 Continued. Geophysical and optical televiewer logs for bedrock wells BC-4D at Bent Creek Research Station, North Carolina.



APPENDIX 2 Continued. Geophysical and optical televiewer logs for bedrock wells BC-5D at Bent Creek Research Station, North Carolina.



APPENDIX 2 Continued. Geophysical and optical televiewer logs for bedrock wells BC-7D at Bent Creek Research Station, North Carolina.



APPENDIX 3. Well-construction details for wells drilled at Bent Creek Research Station, North Carolina.

Well name	Ground water zone	Latitude	Longitude	Date installed	Measuring point elevation	Land surface elevation	Total depth	Cased or open interval	screen/open hole diameter	Well yield (approximate)
					ft msl	ft msl	ft bls	ft bls	in	gpm
BC-1S	transition zone	35.477591667	82.636153333	17-Oct-2002	2203.94	2201.0	22	8 - 23	4	5
BC-1I	transition zone	35.477806667	82.636200000	16-Oct-2002	2205.29	2202.5	53	38 - 53	4	15
BC-1D	bedrock	35.478015000	82.636575000	8-Oct-2002	2204.27	2201.8	221	54.7 - 221	6.25 OH	40
BC-2S	saprolite	35.481786667	82.634983333	30-Oct-2002	2193.65	2190.7	20	5 - 20	4	1
BC-2I	transition zone	35.481701667	82.634858333	24-Oct-2002	2194.61	2191.7	36	21 - 36	4	5
BC-2D	bedrock	35.481588333	82.635120000	23-Oct-2002	2194.74	2190.2	300	53 - 300	6.25 OH	0.5
BC-3S	saprolite	35.482388333	82.636666667	3-Oct-2002	2212.94	2210.1	30	15 - 30	4	0.5
BC-3I	transition zone	35.482500000	82.636611667	3-Oct-2002	2212.51	2209.5	50	35 - 50	4	2
BC-3D	bedrock	35.482361667	82.636695000	17-Sep-2002	2211.81	2209.1	300	61 - 300	6.25 OH	<0.5
BC-4S	saprolite	35.485611667	82.640750000	12-Sep-2002	2262.78	2259.7	22	7 - 22	4	2
BC-4I	transition zone	35.485583333	82.640583333	11-Sep-2002	2261.82	2258.8	41	26 - 41	4	20
BC-4D	bedrock	35.485528333	82.640528333	29-Aug-2002	2261.55	2258.5	501	61 - 501	6.25 OH	10
BC-5S	saprolite	35.486221667	82.642916667	8-Aug-2002	2303	2300.0	24	9 - 24	4	3
BC-5I	transition zone	35.486250000	82.643111667	22-Aug-2002	2304.89	2302.2	47	32 - 47	4	nt
BC-5D	bedrock	35.486111667	82.643028333	12-Aug-2002	2307.42	2304.8	300	62 - 300	6.25 OH	1
BC-6D	bedrock	35.488600000	82.644170000	4-Nov-2005	2363	2360.0	190	55-190	6.25 OH	nt
BC-7S	saprolite	35.490861667	82.644195000	17-Jul-2002	2371.19	2368.2	25	10 - 25	4	1
BC-7I	transition zone	35.490888333	82.644028333	16-Jul-2002	2371.95	2369.0	45	30 - 45	4	1
BC-7D	bedrock	35.490916667	82.644111667	10-Jul-2002	2372.81	2369.9	285	62 - 285	6.25 OH	<0.5
P1S	saprolite	see map on figure 10		16-Jun-2004	2263.21	2260.4	17	12 - 17	2	nt
P1I	transition zone	see map on figure 10		15-Jun-2004	2262.83	2260.0	30	25 - 30	2	nt
P2S	saprolite	see map on figure 10		22-Jun-2004	2255.01	2252.1	22	17 - 22	2	nt
P2I	transition zone	see map on figure 10		23-Jun-2004	2254.95	2251.9	64	54 - 59	2	nt
P3S	saprolite	see map on figure 10		23-Jun-2004	2254.28	2251.4	22	17 - 22	2	nt
P4S	saprolite	see map on figure 10		24-Jun-2004	2235.27	2231.9	17	12 - 17	2	nt
P4I	transition zone	see map on figure 10		24-Jun-2004	2234.78	2232.2	30	25 - 30	2	nt
P5S	saprolite	see map on figure 10		30-Jun-2004	2259.86	2257.1	17	12 - 17	2	nt
P5I	transition zone	see map on figure 10		30-Jun-2004	2259.25	2256.6	29	24 - 29	2	nt
P6S	saprolite	see map on figure 10		13-Jul-2004	2260.96	2257.9	22	17 - 22	2	nt
P6I	transition zone	see map on figure 10		1-Jul-2004	2260.59	2257.7	34	29 - 34	2	nt
P7S	saprolite	see map on figure 10		14-Jul-2004	2274.26	2271.3	13.5	8.5 - 13.5	2	nt
P7I	transition zone	see map on figure 10		20-Jul-2004	2276.06	2273.3	25	20 - 25	2	nt
P8S	saprolite	see map on figure 10		14-Jul-2004	2259.69	2256.7	20	15 - 20	2	nt
P8I	transition zone	see map on figure 10		14-Jul-2004	2259.69	2256.7	34	29 - 34	2	nt

ft, feet; msl, mean sea level; bls, below land surface; OH, open hole; in, inches; gpm, gallons per minute; nt, not tested